Plant Nutrition of Greenhouse Crops

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Contents

Definitions

Adjusted mol weight	mole weight adjusted on residual constituents, defined "molweight", expressed as: mol
C^+	Sum of valences of all cations in a solution, expressed as: mol l^{-1}
c	Ion concentration in a solution, expressed as: mol l^{-1}
CEC	Cation exchange capacity, electric charges on the surface of a material to adsorb cations, expressed as: mol kg^{-1}
EC	Electrical conductivity at 25°, expressed as: dS m^{-1}
Hydroponics	Cultivation in nutrient solution without any substrate other than the propagation material
Inert substrate	Substrate that does not affect the status of the substrate solution as such that specific adjustments are required for compensation
m	mille (10^{-3})
μ	micro (10^{-6})
1:2 volume extract	A specific extract prepared from 2 volumes of water to which so much field moist soil is added that the volume is increased with one volume
Residual salts	Salts accumulated in the root zone of soils or substrates from fertilizers or irrigation water, because of an uptake lower than the addition
Root environment	For soils *in situ* the soil depth in which the majority of the roots will be present. For greenhouses mostly 25 cm. For substrates usually the total substrate volume is taken into account

Salinity threshold	The maximum EC value in the root zone without any yield reduction, expressed as: dS m^{-1}
Soil solution	Solution extracted from soils at field capacity as defined in Section 3.3
Soilless cultivation	Cultivation other than in soils *in situ*
Substrate	Growing medium other than soils *in situ*
Substrate solution	Solution extracted from growing media at field moist condition as defined in Section 3.3
SYD	The slope of the salinity response function for values above the salinity threshold value in percents per unit EC, expressed as: %/dS m^{-1}
Uptake concentration	The ratio between the uptake of a mineral element and the water uptake by the crop, expressed as: mol l^{-1}
VPD	Vapour pressure deficit, expressed as: kPa

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Fig. 11.5	After Adams (2002). Modified after permission of Embryo Publications
Table 12.3	Reprinted by permission of the International Society Horticultural Science
Table 12.4	Reprinted after permission of Embryo Publications
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Chapter 1
Greenhouse Horticulture

1.1 Introduction

Greenhouse cultivation has a long history and it is difficult to appoint where the first greenhouse was built. Such an appointment directly is hindered by a good definition of a greenhouse. However, independent of a precise definition, undoubtedly, one or more orangeries at castles or palaces will be mentioned, but no one can testify whether it really can be considered as the first greenhouse. The first developments of greenhouses focussed on commercial production of vegetables, fruits and flowers are dated at in the end of the 19th century and occurred mainly in the North-West area of Europe. In advance the production of the crops in greenhouses was mainly connected with the demand in the market for early fruits and vegetables. Another line in the development of greenhouses was the production of crops that could be grown hardly or not at all in the cool and wet climate conditions of North-West Europe.

At first the greenhouses were situated merely in areas of moderate climate throughout the year. This means climates where the temperatures do not fall too much below zero, to prevent crops from freezing during winter and where the temperatures do not rise too much during summer to avoid extremely high temperatures inside the greenhouse. Therefore, many greenhouse districts initially developed in coastal areas and on islands. The greenhouse area in the Westland district in The Netherlands and the greenhouses situated on the British Channel Islands were good examples of such developments.

After the Second World War, with the development of the European Community and the improvement of the transport, the greenhouse industry in North-West Europe was adversely affected by the competition of products from the Mediterranean countries. At that time many agricultural experts predicted that the greenhouse industry in North-West Europe would lose the competition with the South and finally should disappear and be taken over by field production in the Mediterranean areas. These expectations were merely based on the development of the North-American situation, where the vegetable production was situated in California and other Southern parts of the country in open fields and the big North-East market was supplied with fresh vegetables by road transportation. Up till now, in Europe the mentioned

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expectations did not come true. On the contrary, at the end of the 20th century greenhouse horticulture was a growing business all over the world and there are sufficient arguments to suggest that this development will be continued in the 21st century in many countries.

The strong development of greenhouses growing all over the world as came about in the second half of the 20 th century was affected by many factors. Among these following are mentioned as being the most important.

- Development of greenhouse construction. The simple glass construction like the lay flat systems and the wooden greenhouse constructions were replaced by metal constructions, possible furnished with heating and cooling systems suitable for a fully automatic climatic control.
- Breeding of new cultivars due to greenhouse cultivation of crops already grown in greenhouses and the increasing diversity of crops grown in this branch. The breeding of new cultivars contributed to increased yield, improved quality and diversity within a produce.
- The development of auxiliary systems, as used in modern greenhouses for climate control, irrigation, fertilization, biological pest control and growing technique.
- Substrate growing which ensured a better control of the root environment. The small root volume introduced with this growing method strongly improved the management of factors affecting the root development and root functions.
- Flexibility of the branch on the demand of the market and on the competition of products from elsewhere. This means quick adjustments on the demand and quick changes to a different product when the competition from elsewhere cannot be met.
- Successful operations of the greenhouse industry in increasing yields and decreasing costs. In this way the costs per unit produce was stabilized or increased only gradually.

Originally, the greenhouse industry operated in a supply market only, as was common for other agricultural branches. But with the improved transport abilities in the second half of the 20th century many horticulture products were transported from anywhere to all parts of the world. Thus, from this view point horticulture production in greenhouses had no longer arguments to operate as a supply market. The products of the greenhouse industry joined in free competition with field grown products from all over the world. In this way the greenhouse industry developed into a horticultural activity ready to be operative in the consumer market and to bring better and cheaper products on the market than those from the open field.

Many greenhouse products have a luxurious image, which especially is the case for greenhouse flowers. In this way the greenhouse industry has a strong relationship with living standards. Markets like this are characterized by diversity, quality and immediate answers to the demands of customers. The high demands on quality of such markets are not restricted to the product itself, but include also the production methods. Therefore, the greenhouse industry more and more will be confronted with factors like the environmental consequences of the production method and the conditions for the workers during the process. Increasing search for sustainable growing methods and a high standard for the conditions under which the work is carried out belong to the quality requirements as well.

1.2 Fertilization in Greenhouse Industry

In contrary of many other agricultural activities the costs of fertilization in the greenhouse industry are relatively low and amount to only a few percentages of the total costs. Thus, from economic view points were no arguments for a precise and careful application of plant nutrients. In the past an abundant use of fertilizers in the greenhouse industry was common practice and there was no interest by the growers to limitations in the use of fertilizers to prevent in this way the leaching of nutrients to the environment. However, in the last decades of the 20 th century environmental pollution became a subject of permanent attention by the governments of North-West European countries and was quickly followed by regulations from the European Community.

Measurements by the Dutch greenhouse cultivation learned that substantial quantities of nutrients can be transported to the deep ground water or surrounding surface water like ditches, canals and rivers. In Table 1.1 some data is summarized about nutrient leaching from greenhouse. The data is derived from studies carried out under conditions that not yet regulations were issued, roughly 1975−1980. Tomatoes were grown in soil as well in substrate systems; the soil was clayey loam and the substrate rock wool. The N mentioned with the residual factor reflects the undetected quantity, added but not traced within the study. One of the factors responsible for this undetected quantity, for example can be de-nitrification of N. The N efficiency was low, especially for the soil grown situation and the discharge of minerals to the environment high and estimated as unacceptable. Therefore, in the last decades of the 20th century extended studies were carried out to factors contributing to a minimum discharge of minerals, like the restrictions on the fertilizer use and an efficient water supply.

Besides the supply of minerals indeed restrictions on the quantity of drainage water played an important part in this field. However, restrictions in this field will

Table 1.1 Balance sheets of water and N as presented by Sonneveld (1993) for tomato growing in greenhouses under free drainage conditions. The quantities of water are expressed as m^3 ha^{-1} $year^{-1}$ and the N as kg ha^{-1} $year^{-1}$

	Soil grown crop		Substrate grown crop	
Factors	Water	N	Water	N
Addition	12,950	2269	9691	1935
Uptake by crop	6700	609	7600	1110
Discharge by drainage	6250	1344	2091	825
Residual factor	0	316	0	0
Efficiency	0.52	0.27	0.78	0.57

cause problems with accumulation of salts and an unequal distribution of the moisture content in the soil. For substrate growing the problem was met by reuse of the drainage water and for soil grown crops by a switch to substrate cultivation or by an improvement of the supply of water and fertilizers. Reuse of drainage water and a more precise irrigation pattern strongly aggravate the salt accumulation in the root zone and set high demands on the water quality. These developments will be discussed in the proper chapters.

1.3 Nutrient Uptake

Despite a precise application and an efficient utilization of nutrients in the modern greenhouse industry, the required additions of nutrients will stay high in this horticultural branch. This is related to the high yields usually gained in greenhouses. Between the yield of crops and the uptake of nutrients often a close linear relationship was found, like shown for tomato and chrysanthemum in Fig. 1.1. The relationships shown for both crops differ strongly. This can be explained by several factors, of which are the most important ones: the characteristics of the crops, the mutual ratios of the ions in the external solution, the growing period, and the definition of the yield. Greenhouse crops are generally grown at high external nutrient concentrations and realise under these conditions an optimal nutrient status in the plant. A nutrient status in the external solution higher than required does not significantly affect the uptake (Sonneveld and Welles, 2005). However, the mutual ratios in the external solution of the ions will affect the uptake of a specific ion. The definition of the yield is also important. In the given examples for tomato the weight of the harvested fruits is defined, while for chrysanthemum the total weight of the shoots at harvest is taken into account. Furthermore, the growing period of a chrysanthemum

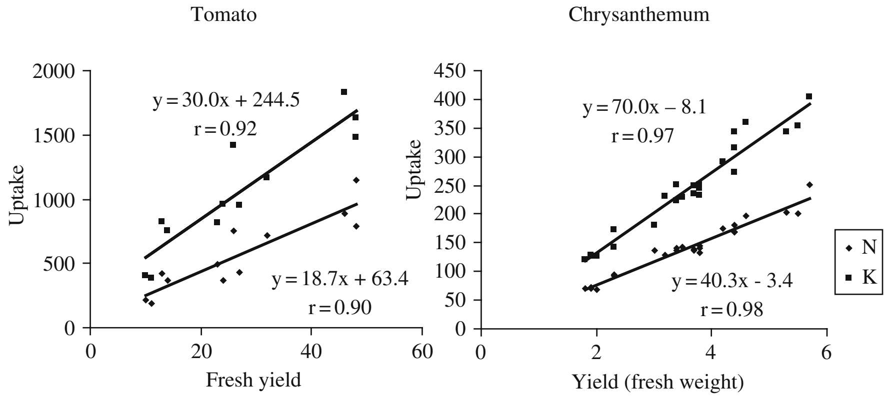

Fig. 1.1 Relationships between the yield of tomato and chrysanthemum (kg m^{-2}) and the uptake of N and K (kg ha^{-1}). The yield of tomato is expressed as fresh fruit production and those of chrysanthemum as the weight of shoots harvested

crop in greenhouses is much shorter than those of a tomato crop. Under the growing conditions in North-West Europe the duration of the growing periods are 11 and 3 months for tomato and chrysanthemum, respectively. Thus, annually one tomato crop will be grown, while for chrysanthemum over 4 crops are normally practiced. The annual uptake calculated with the data for a high yielding tomato crops will easily amount to 1100 kg N and 2000 kg K per ha and for a chrysanthemum cropping 700 kg N and 1100 kg K per ha, being quantities that strongly exceed the uptake of any field crop.

Besides the quantities of minerals absorbed by greenhouse crops, the ratios also will differ from those in the field. Marschner (1997) whose calculations are mainly based on data from Epstein (1965) presented average mole ratios between elements absorbed by plants sufficient for an adequate growth. This data was required from some field crops and he pointed out that the ratios between crops will considerably vary depending on the plant species. In comparison with the data presented by Marschner, ratios of mineral uptake by three greenhouse crops are presented in Table 1.2. The calculations were made for cucumber, lettuce and rose as being a vegetable fruit crop, a leafy vegetable crop and a flower crop, respectively. The data for greenhouse crops are mainly based on the results of De Kreij et al. (1992) and Sonneveld (1997). The differences between the greenhouse crops are substantial for some elements. Compared with the data of Marschner the most striking differences have been found for the generally high ratios for the elements K, Ca, P and S and the generally low ratios for Fe, Mn and Cu. The ratios for Mo greatly vary for the greenhouse crops presented and are high in comparison with the data of Marschner. The information about the uptake of this element for greenhouse crops is restricted and the relatively high ratios for these crops possibly can be explained by accidental additions of this element in the fertilization programmes. The required quantities of Mo are not yet exactly determined for greenhouse crops (Bloemhard and Van der

Table 1.2 Mol ratios of the average concentrations of mineral nutrients as absorbed by some greenhouse crops compared with the data of field crops as presented by Marschner (1997)

		Greenhouse crops		
Element	Field crops	Cucumber	Lettuce	Rose
N	1,000,000	1,000,000	1,000,000	1,000,000
K	250,000	568,000	604,000	359,000
Ca	125,000	247,000	168,000	174,000
Mg	80,000	82,000	52,000	57,000
P	60,000	92,000	94,000	76,000
S	30,000	65,000	43,000	73,000
B	2000	2000	1000	1600
Fe	2000	800	1000	800
Mn	1000	600	430	600
Zn	300	240	290	240
Cu	100	60	57	80
Mo	1	8	2	12

Lugt, 1995). Optimal concentrations mentioned in the literature differ strongly and young plants sometimes require higher concentrations than old ones (Roorda van Eysinga and Smilde, 1981).

1.4 Fertilization Programmes

In the past fertilization and irrigation in greenhouses was based on the experiences of growers. The addition of farm yard manure and other natural organic products was common practice, supplemented with fertilizers used for field crops. Often these fertilizers contained high NaCl contents. Formerly, this was mostly not a problem for field crops, because of the surplus of the precipitation in winter, by which the salt residues were leached from the root zone. However, since the natural precipitation was excluded by the greenhouse constructions salts could easily accumulate in the greenhouse soils to levels that reduced the growth of many crops. The salts accumulated during cultivation, especially in the top layers in the greenhouse soils, like shown in Table 1.3 (Van den Ende, 1952). The high salt content in the top layer at the end of the cropping period was a major hindrance for the start of a new crop. Therefore, such soils must be flooded before a new crop could be started. The salinity problem as presented resulted to special requirements for the irrigation and the fertilization in greenhouses, like the development of fertilizers with low residual salt contents better suited for the greenhouse situation and the development of irrigation systems with which it was possible to supply the crops with ample water during crop growth. With these new developed irrigation systems it was not only possible to wash out the residual salts from the soil after the cropping period, but it seemed possible to prevent high salt accumulations in the soil with an ample water supply during the cropping period. With the use of fertilizers easily soluble in water, the step to the addition of these fertilizers to the irrigation water was simple and the application of the so called fertilizer diluters was quickly established. By these systems the term fertigation was born and the addition of fertilizers in combination with the irrigation water became common practice.

The basis for a well controlled application of fertilisers to the irrigation water originated from the measurement of the electrical conductivity (EC) in flowing water streams by an apparatus placed on commercial greenhouse holdings in The

Table 1.3 NaCl contents of a clayey loam greenhouse soil over different depths at the end of a cropping period and after a flooding with 300 mm water. NaCl contents in mmol kg^{-1} dry soil

Depth	End of cropping	After flooding
0–5	87	3
5–10	30	6
10–15	15	6
15–20	12	6
20–25	12	5
25–30	12	6

After van den Ende (1952).

Netherlands. These so called "concentration meters" expressed the fertilizer concentration in the irrigation water as EC values (Sonneveld and Van den Ende, 1967). This manner of measurement of salt concentrations had already been practiced on laboratory level for many years, but had never been practiced in this way on greenhouse nurseries. Since that time, the measurement of the EC has become important as a determination for the total ionic concentrations in different solutions. Examples are the determinations of the EC in irrigation waters, in fertilizer solutions, in nutrient solutions, in drainage waters, and in soil and substrate extracts. Used in this way the determination of the EC became an important parameter for the control of fertilization management in the greenhouse industry. Another important factor in the management of the fertilization in the greenhouse industry was the development of soil testing methods, based on water extraction (Van den Ende, 1952). Originally, soil testing in greenhouses was used to check the salt and nutrient status on a yearly basis. The strong changes in the chemical composition of greenhouse soils and the increasing nutrient absorption of the crops resulted from the increasing yields introduced the need for a more frequent check on the nutrient status of the soil. Therefore, the so called "top dressing" samples were introduced as supplemental information about the development of the nutrient status of the soil during cultivation. The greenhouse soils, for example, were sampled and analysed every month and the application of fertilizer to the irrigation water was appointed on basis of this data. At the Glasshouse Crops Research Station at Naaldwijk, The Netherlands was an early eye for the development of a systematic fertilization on basis of such data, because in the beginning the greenhouse soil samples were analysed in a laboratory connected to this research station. The combination of plant nutrition research and the development of routine soil testing methods became a fruitful basis for the design of fertilization systems for greenhouse soils. Such systems have been developed by researchers of various research stations in The Netherlands, in cooperation with the workers of the advisory service (Breimer et al., 1988) and was made available for a wide range of crops and growing conditions (IKC, 1994).

The development of fertilization support systems especially was enlarged with the growing interest for substrate cultivation and it appeared to be a cultivation method for practical applications. The small root volumes used with this growing method are responsible for tremendous fluctuations in the salt and nutrient status of the root environment. Sonneveld (1981) calculated that in substrate systems in the root environment momentarily only few percentages are present of the total minerals required by the crop grown. Since then, the yield of the crops and along with this the mineral uptakes are strongly increased, while the substrate volumes made available to the crops and thus, the storage of minerals available in the root environment are only decreased. Utmost, the algorithm for the calculation of a nutrient solution for substrate growing is complicated, because all essential elements, at the least 14, must be taken into account. Such an algorithm is suitable for computerizing and the necessary outlines were presented (Sonneveld et al., 1999). Together with the results of an intensive control on the composition of the nutrient status in the root environment fully automatic systems for the nutrient supply of substrate grown crops have been designed. The necessity for an intensive control on the nutrient supply in substrate systems was accentuated in the last decades of the 20th century by the restrictions and regulations on emission of minerals to the environment. These developments strongly stimulated research to reduction of environmental pollution and the reuse of drainage water came into being on large-scale in substrate cultivation (Voogt and Sonneveld, 1997). In such systems, possible deviations from the optimum composition of nutrient solution in the root environment are not yet alleviated by the discharge of the drainage water, but are brought back into the system. Thus, depletions and accumulations easily occur in such systems and necessitate precisely tuned programmes, an intensive control on the salt and nutrient status in the root environment and a frequent feed back of the analytical data to the algorithm.

Parameters for the different systems used in the greenhouse industry are a broad view on the needs of minerals of greenhouse crops and the relations between the uptake of the different elements on the one hand and the nutrient status in the root environment on the other hand. Furthermore, the interactions of these relationships with the growing conditions, like irrigation, climate and type of soils and substrates are numerous and play an important role in the fertilization management.

In the greenhouse industry the nutrient status in the root environment is merely characterized by the composition of the soil solution and the substrate solution. The composition of these solutions sometimes can be determined by analysis of the solution directly from the field moist soil or from the substrate. When this is not possible or when it is too laborious the composition can be estimated by water extraction. Exchangeable quantities of nutrients are of secondary importance, because of the generally high nutrient status maintained in the root environment of greenhouse grown crops, while the interpretation of such data is more complicated than those derived from water extraction. The relationships between exchangeable nutrient concentrations in soils and substrates and the uptake by plants depend strongly on the adsorption capacity and the character of the adsorption complex of the soil and the substrate in which the plants are grown (De Vries and Dechering, 1960; Mengel and Kirkby, 1987; Roorda van Eysinga, 1965; Sonneveld and De Kreij, 1995).

1.5 Development of Greenhouse Horticulture

Last decades of the 20th century the greenhouse horticulture in high technological developed countries is characterized by a rapid changing technology with a degree innovative power. The technological applications were not solely directed on extension and higher productions, but primarily on the sustainability of the greenhouse industry. In this development main focuses were quality improvement of the produce and strong reductions on the environmental impact. With respect to last item, three subjects accompanied the research in the greenhouse industry: reduction of the use of energy, reduction of the use of plant protection chemicals and reduction of the emission of minerals, focussed on N and P. Solutions in these directions were found in high technological developments, like for example increasing yields, storage of energy over seasons, use of residual heat, co-generation of electricity, biological control of pests and diseases, and reuse of drainage water for substrate grown crops. The use of substrates in the greenhouse horticulture often has been

Picture 1.1 Modern greenhouses in The Netherlands

Picture 1.2 Greenhouses with plastic cover at the Mediterranean coast in Almeria Spain

criticized as "unnatural" and "industrial". However, it is just the industrial character that supplies excellent opportunities for further improvements to restrict environmental pollutions. Such developments true enough are developed and applied in a high technological greenhouse industry like exists in North-West Europe, North-America, Australia and Japan, but this does not mean that parts of this knowledge cannot be applied in less technological developed greenhouse cultivation, like

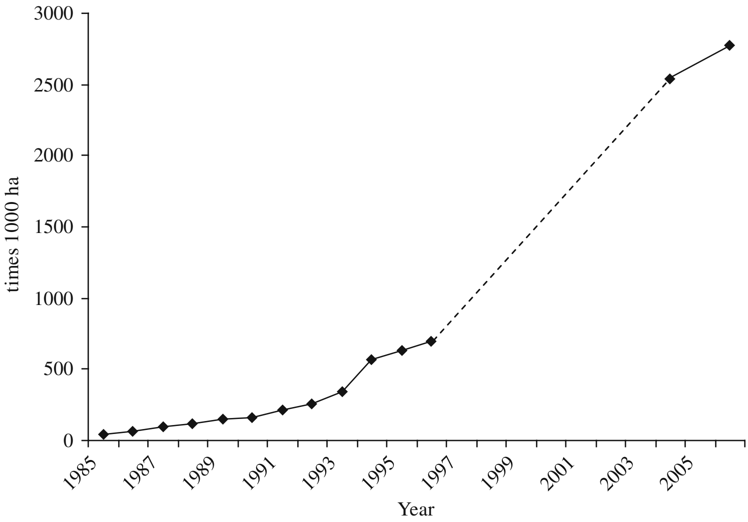

Fig. 1.2 The development of protected cultivation in China during the years 1985 till 1996. The areas concerned are tunnels and greenhouses, mainly covered by plastic. After Zhang (1999), and until 2006 following personal information of Zhang (2007, Personal information by e-mail)

Table 1.4 Areas (ha) of protected cultivation in the Mediterranean area in 2001

Type of greenhouses	Areas
Large plastic tunnels	168,265
Glasshouses	21,800
Low Tunnels	140,600
Total	330,665

After Pardossi et al. (2004).

protected cultivations under plastic. The development of protected cultivation under plastic is a strongly growing agricultural activity all over the world. The development of this type of protected horticulture in China is a good example of this. The development in this country, presented in Fig. 1.2 (Zhang, 1999), concerns mainly plastic tunnels and greenhouses. The figure shows the tremendous areas of protected cultivation that can be developed in short time when use is made of plastics. About 75% of the areas were tunnels and 25% greenhouses. The development in Europe is quite different. In the Mediterranean areas relatively more greenhouse constructions were found. The greenhouses amounted to 55% and the tunnels 45%, like shown in Table 1.4 (Pardossi et al., 2004). From the greenhouse constructions in the Mediterranean area about 10% is covered with glass, while in North-West Europe just only glass is used as cover on the greenhouses. Such differences have beside an economic reason also a technical basis. The low light intensity in North-West Europe requires maximum light transmission and this is much better with a glass than with a plastic cover.

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Chapter 2
Fertilizers and Soil Improvers

2.1 Introduction

In greenhouse industry fertilizers as well as soil improvers are widely used. Fertilizers are mainly applied to optimize the physical-chemical conditions of the root environment and are used for growing in soils in situ as well as for growing in substrates. Soil improvers are materials solely added to soils in situ primarily to maintain or improve its physical properties, but it also can improve its chemical and biological properties. Thus the difference between fertilizers and soil improvers is somewhat diffuse.

The optimization of the physical-chemical conditions by addition of fertilizers is focussed on the improvement of the availability of nutrients, and on control of the pH and the osmotic potential in the root environment. Since growth rate of crops and as a result yields are very high in greenhouses, the removal of nutrients is substantial. Thus, the application of most fertilizers is primarily essential to restore the nutrient status of the root environment. The pH level is controlled by the addition of specific fertilizers, but is also affected by the addition of the fertilizers added to improve the nutrient status. Upside down, the fertilizers used to control the pH contain nutrients, usually Ca and Mg. Control on the osmotic potential is realised by addition of extra fertilizers to decrease this value in the soil solution. A decreased osmotic potential (increased EC value) is sometimes required to reduce lush growth of crops under poor light conditions or to improve the quality of the harvested produce, being favourable effects of a decreased osmotic potential.

Soil improvers are usually applied as base dressing, whereby the nutrients added with them are taken into account with the application of the fertilizers required for the base dressing. Not al the nutrients in soil improvers are directly available. The N is gradually released during decomposition of organic matter and will be not taken into account directly with the addition. Fertilizers are used as base dressing as well for top dressings; they are applied for broadcasting as well for fertigation. In the greenhouse industry a vast quantity of the fertilizers is added as top dressings by fertigation, while with cultivation in substrates more or less all fertilizers are applied by fertigation. Therefore, the development of fertilizers due to fertigation has assumed substantial proportions, which resulted in a broad assortment of fertilizers suitable for this working method.

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In the following sections the composition and the application of different fertilizers used in the greenhouse industry will be discussed. Some materials used as soil improver also are used with the preparation of growing media. In the last case it is not defined as a soil improver, but as a growing medium constituent. In that capacity the use will be discussed in the chapter about the preparation of growing media, Chapter 11.

2.2 Fertilizers

In this section a review will be given of the fertilizers commonly used in greenhouse horticulture. The choice of the fertilizer types used in greenhouse industry sometimes differs from those for field crops, because of the fact that the choice for field crops is strongly determined by the price of the fertilizer. This scarcely is a factor in the greenhouse industry, because fertilizer costs represent only a minor fraction of the total costs of greenhouse industry. The characteristics on which the choice of fertilizers is based are high solubility and low residual salt contents. Furthermore, many fertilizers in the greenhouse industry are used for fertigation of soil grown crops and substrate cultures and therefore, must be free from insoluble material. Such residues are not harmful to crops, but enhance the clogging of drip irrigation systems used for fertigation. For fertigation with sprinkler systems, the blocking of the nozzles is less a problem, but insoluble residues easily precipitate on the crop which is visible as a residue on the produce.

The fertilizer industry often expresses the nutrient contents of fertilizers as oxides, like K_2O and P_2O_5. This way of expression has a historical basis, but generally fertilizers do not contain any oxides. However, in greenhouse horticulture more and more the nutrients are expressed as elements. For many purposes it is easier to work with mole weights, like with the calculation of nutrient solutions for substrate culture in Chapter 12. Therefore, in the present chapter besides the information supplied by the fertilizer producer about nutrient contents expressed as oxides also elemental contents and where informative mole weights will be given. The mole weights are calculated as defined by the international system of units Aylward and Findlay (1974). In some cases fertilizers are not made up of a single salt or compound, but contain residual constituents. This for example is the case with dissolved fertilizers, which self-evidently contain water as a constituent. In other cases the impurity of the compound plays a part. In such cases an adjusted mole weight will be calculated bases on the essential element or compound of the fertilizer in question. Such molweights will be reflected between quotation marks, like “molweight”. A list of rounded atomic weights used in this book is added in Appendix A. The elemental contents are calculated on basis of following formula.

$$\%K = \frac{39.1}{47.1}\%K_2O \tag{2.1}$$

$$\%P = \frac{62}{142}\%P_2O_5 \tag{2.2}$$

$$\%Ca = \frac{40.1}{56.1}\%CaO \tag{2.3}$$

$$\%Mg = \frac{24.3}{40.3}\%MgO \tag{2.4}$$

$$\%S = \frac{32.1}{80.1}\%SO_3 \tag{2.5}$$

Beside the solid mineral salts, some fertilizers are available in soluble form. The percentage nutrients and the adjusted mole weight of such solutions depend on the concentration of the mineral salt in charge. They will be calculated with following formulae.

$$\%Nu_{sol} = \%Nu_{solid}Fraction_{salt} \tag{2.6}$$

In which

% Nu_{sol}= nutrient content in the solution in %
% Nu_{solid}= the nutrient content in the solid form in %
$Fraction_{salt}$= the fraction mineral salt in the solution

$$\text{“}molweight_{sol}\text{”} = \frac{molweight_{solid}}{Fraction_{salt}} \tag{2.7}$$

In which

$molweight_{sol}$= mole weight of the soluble form
$molweight_{solid}$= mole weight of the solid form
$Fraction_{salt}$ as defined under (2.6)

Among the fertilizers presented also some hydroxides, acids and carbonates are included. The less soluble forms of these chemicals are used in the greenhouse industry for pH adjustment of soils and substrates, while the soluble forms are used in fertilizer recipes and for the pH adjustment of nutrient solutions for substrate cultures. Acids are sometimes also used for adjustment of the pH of irrigation water with a high HCO_3 concentration, when used for drip irrigation of soil grown crops.

2.2.1 N fertilizers

N fertilizers used in greenhouse cultivation contain N as NO_3, NH_4 or urea. For growing in soil all forms are used, while for substrate growing mainly NO_3 is applied and NH4 also in small quantities. Urea is not used in substrate cultivation, because in substrate solutions urea will survive rather long and can be toxic to plants. Sometimes urea is used for pH stabilisation in the water used with drip

Table 2.1 N fertilizers used in greenhouse industry

Fertilizer	Chemical formula	% N	% others	Mole weight
Ammonium nitrate	NH_4NO_3	35		80
Nitrochalk	$NH_4NO_3 + CaCO_3$	21–27		
Ammonium nitrate solution	NH_4NO_3	35[1]		80[1]
Ammonium sulphate	$(NH_4)_2SO_4$	21	24 S	132.1
Calcium nitrate	$5[Ca(NO_3)_2.2H_2O].NH_4NO_3$	15.5	18 Ca	1080.5
Calcium nitrate solution	$Ca(NO_3)_2$	17[1]	24 Ca[1]	164.1[1]
Urea	$CO(NH_2)_2$	46		56
Nitric acid solution	HNO_3	22[1]		63[1]

[1]For the pure chemical. Real value depends on the strength of the solution, see text.

irrigation of potted plant cultures. In substrate growing NH_4 especially is added to nutrient solutions to control the pH, see Section 13.4. On calcareous soils the use of urea as well NH_4 is also effective for adjustment of the pH which is discussed in Section 15.7. In Table 2.1 a review is given of the N fertilizers commonly used in greenhouse industry.

2.2.2 P fertilizers

The P fertilizers used in greenhouses primarily consist of orthophosphates. The cheapest and most widely used forms are the Ca salts, from which only the mono form has a high solubility. The low concentrated fertilizers of this form contain a lot of gypsum and therefore, are seldom used in greenhouses. Calcium orthophosphates are never used for fertigation and substrate cultures, because these fertilizers mostly contain too much insoluble components. For greenhouse industry suitable P fertilizers are listed in Table 2.2.

Most P fertilizers contain F, which is toxic to some mono-cotyledon plants, especially many bulb and tuber crops, from which freesia is the most well known greenhouse crop (Roorda van Eysinga, 1974). For crops sensitive to F toxicity P fertilizers with a low content of F are on the market. Di-calcium phosphate ($CaHPO_4$) prepared for cattle feed is such a fertilizer, however, solely suitable for broadcasting. Some other P fertilizers are also produced with a low F content, which will be indicated on the packing.

In substrate cultivation beside H_3PO_4 completely soluble salts like $NH_4H_2PO_4$ and KH_2PO_4 are used. Recently the use of specific polyphosphates is introduced by some fertilizer producers. The main object of the use of polyphosphates is prevention of precipitation of Ca and Mg from the irrigation water and by this lessening of clogging of the irrigation system. The chemical formulations of these compounds are kept secret up till now. The concentrations recommended varies between 0.25 and 0.50 mmol P l^{-1} water.

Table 2.2 P fertilizers used in greenhouse industry

Fertilizer	Chemical formula	% P_2O_5	% P	% others	Mole weight
Super phosphate	$Ca(H_2PO_4)_2$	46	20	± 10 Ca	
Mono potassium phosphate	KH_2PO_4	51	22	28 K	136.1
Mono ammonium phosphate	$NH_4H_2PO_4$	60	26	12 N	115
Phosphoric acid	H_3PO_4	72[1]	32[1]		98[1]
Dicalcium phosphate	$CaHPO_4$	46	20	± 25 Ca	
Poly phosphate	Super FK[2]	16	6.7	22 K	
	Vitaphoska[2]	31	13	41 K	

[1]For the pure chemical. Real values depend on the strength of the solution, see text;
[2]trade marks, chemical composition not published.

2.2.3 K fertilizers

K fertilizers are listed in Table 2.3. For broadcasting with base dressings mostly the SO_4 salt is used. KCl is never used for soil grown crops in greenhouses. It is only used for special applications in substrate cultures, as a replacement for NO_3 when Cl is required in the nutrient solution and the concentration in the primary water is very low. To this purpose a very pure form is desired, because the Na content must be very low.

Table 2.3 K fertilizers used in greenhouse industry

Fertilizer	Chemical formula	% K_2O	% K	% others	Mole weight
Potassium sulphate	K_2SO_4	54	45	18 S	174.1
Potassium magnesium sulphate[1]	$K_2SO_4.MgSO_4$	29	24	20 S, 6 Mg	
Potassium nitrate	KNO_3	46	38	13 N	101.1
Potassium chloride	KCl	62	52	48 Cl	74.6
Potassium hydroxide	KOH	84[2]	70[2]		56.1[2]
Potassium bi-carbonate	$KHCO_3$	47	39		100.1
Potassium carbonate	K_2CO_3	68	56		138.2

[1]Qualities can differ, with minor deviations in nutrient contents;
[2]for the pure chemical. Real values depend on the strength of the solution, see text.

2.2.4 Mg fertilizers

Mg fertilizers used in greenhouse industry are listed in Table 2.4. Kieserite is the cheapest form of magnesium sulphate, but it is slowly soluble in cold water. Therefore, this fertilizer is solely used for broadcasting applications. Epsom salt is used when prompt dissolution is required, like for example with fertigation and the

Table 2.4 Mg fertilizers used in greenhouse industry

Fertilizer	Chemical formula	% MgO	% Mg	% others	Mole weight
Kieserite	$MgSO_4.H_2O$	27	16	21 S	
Epsom salt	$MgSO_4.7H_2O$	16	10	13 S	246.4
Magnesium nitrate	$Mg(NO_3)_2.6H_2O$	15	9	11 N	256.3
Magnesium nitrate solution	$Mg(NO_3)_2$	27[1]	16[1]	19 N[1]	148.3[1]

[1]For the pure chemical. Real value depends on the strength of the solution, see text.

preparation of nutrient solutions. When low SO_4 is wanted in nutrient solutions for substrate culture, the nitrate form is used. However, $Mg(NO_3)_2.6H_2O$ is very hygroscopic and thus mostly delivered as a concentrated solution.

2.2.5 Ca fertilizers

Many of the Ca fertilizers has a double function when used in soil growing, because these fertilizers are used as pH control in the soil. This is the case for $CaCO_3$ and $Ca(OH)_2$. They are also used for growing media to enhance the pH of acid substrate constituents, like peat and bark. $Ca(OH)_2$ is better soluble than $CaCO_3$, and thus sometimes used when a quick pH raise is wanted. $CaCO_3$ is the common form used for pH control. Many carbonates contain besides $CaCO_3$ also $MgCO_3$. The ratio between both components varies and depends on the requirements of the soil on Mg, a suitable form can be chosen. In Table 2.5 different Ca fertilizers are presented.

Liming of soil and growing media constituents induce following reactions depending on of the type of liming material.

$$Ca(OH)_2 + 2H_3O \rightarrow Ca + 4H_2O \tag{2.8}$$

$$CaCO_3 + 2H_3O \rightarrow Ca + 3H_2O + CO_2 \tag{2.9}$$

When Ca in a soluble form is desired, mostly $Ca(NO_3)_2$ is used, see Table 2.1. In some situations $CaCl_2$ is suitable instead of KCl for substrate grown crops.

Table 2.5 Ca fertilizers used in greenhouse industry

Fertilizer	Chemical formula	% CaO	% Ca	% others	Mole weight
Slaked lime	$Ca(OH)_2$	75	54		74.1
Limestone	$CaCO_3 + MgCO_3$	55[1]	39[1]	0–11 Mg[1]	
Calcium chloride	$CaCl_2.2H_2O$	38	27	47 Cl	147.1

[1]Maximum values, dependent on the type of lime stone that is used.