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Chapter 2

Fertilizers and Soil Improvers

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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.

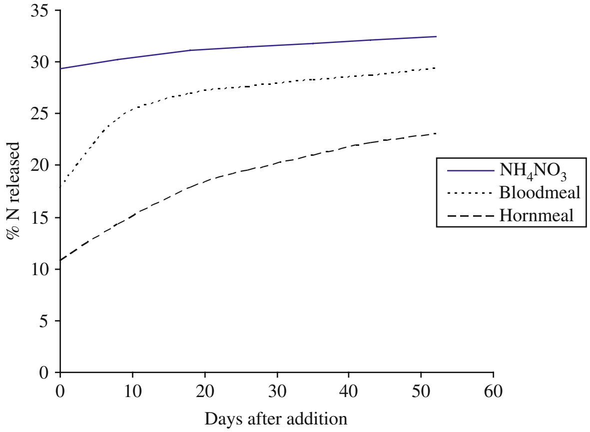

Fig. 2.2 Release of N from waste products of meat industry in an incubation experiment with greenhouse soil in comparison with mineral fertilizer (Proefstation, 1954)

2.2.11 Organic Fertilizers

Organic fertilizers are produced from animal or plant material and are for that reason popular in the organic horticulture. They are sometimes used for traditional soil grown crops and to some extent as an amendment in organic substrates. There is a broad variety of source, some of these fertilizers are prepared from single protein-like materials such as blood and slaughterhouse wastes, while others are prepared from animal manures or industrial biomass wastes. Some fertilizers are formulated with specific nutrient ratios from various sources and put into the market as organic fertilizer compounds. All these fertilizers have in common that the majority of the N and partly also P is present in organic form and is released gradually through decomposition by microbial activity of the soil. The rate of this so called mineralization process differs strongly among different products. As is clear from the data presented in Fig. 2.2, where the release of N is shown for blood meal and horn meal in comparison with NH_4NO_3 (Proefstation, 1954). This process also depends strongly on temperature, humidity, pH and available NO_3 in the soil. Some generally used organic fertilizers are listed in Table 2.8, together with the origin and the contents of major elements.

Table 2.8 Composition of some generally handled organic fertilizers produced from waste materials. The elements are expressed as mass %

Fertilizer	Constituents	N	P	P_2O_5	K	K_2O
Blood meal	Slaughterhouse blood	13	0	0	0	0
Bone meal	Slaughterhouse bones	5	7	16	0	0
Feather meal	Feathers and claws of chicken	13	0	0	0.4	0.5
Cow pellets	Cow manure	1.9	0.4	1	2.2	2.7
Chicken pellets	Chicken manure	2.2	0.3	0.8	1.0	1.2
Malt pellets	Brewery waste	5	1.4	3.1	4.0	4.8
Ricinus pellets	Castor oil industry waste	4	0.7	1.5	6.6	8
Vinasse potassium	Sugar beet industry	2	0	0	23.7	28.6

2.3 Soil Improvers

2.3.1 Organic Matter and Physical Characteristics of Greenhouse Soils

The physical characteristics of soils are mostly not a restriction for the employment of protected cultivation. In The Netherlands for example greenhouse industry is situated on very different soil types. In a series of 75 soil samples from greenhouses in The Netherlands the mass fraction organic matter of oven dried soils varied between 0.03 and 0.61, while the mass fraction clay (particles <0.002 mm) varied between 0.03 and 0.40 (Sonneveld et al., 1990). Furthermore, a relatively high salt content, mostly in combination with a high content of soluble Ca keeps the soil in a crumbly and flaky condition (Hilgard, 1919). The intensive tillage stimulates a loose structure further on. Therefore, the bulk densities of greenhouse soils mostly are lower than those of field soils. Between the fraction organic matter, determined by loss on ignition and the bulk density of greenhouse soils exists a closely relationship, like shown in Fig. 2.3 (Sonneveld, 1990). The characteristics of the relationships found for greenhouse soils and field soils are equal, but the parameters differ. This is shown in Fig. 2.4, where the relationship between the organic matter (loss on ignition) content of the 75 Dutch greenhouse soils of Fig. 2.3 and the bulk density is shown in comparison with the relationship found for these characteristics of field soils (Kortleven, 1970). It is understandable that the bulk density is strongly affected by the organic matter content, because the density of the mineral fraction is much higher than those of the organic fraction (Kipp et al., 2000; Klute, 1986). The functions for the relationships presented in Fig. 2.4 are following.

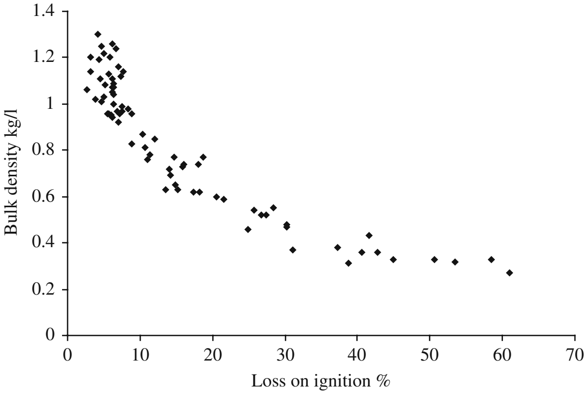

Fig. 2.3 Relationship between the % loss on ignition and the bulk density of greenhouse soils after Sonneveld (1990). *Reprinted by permission of Marcel Dekker*

For greenhouse soils:

$$\rho = \frac{1}{4.67 f_l + 0.69} \tag{2.10}$$

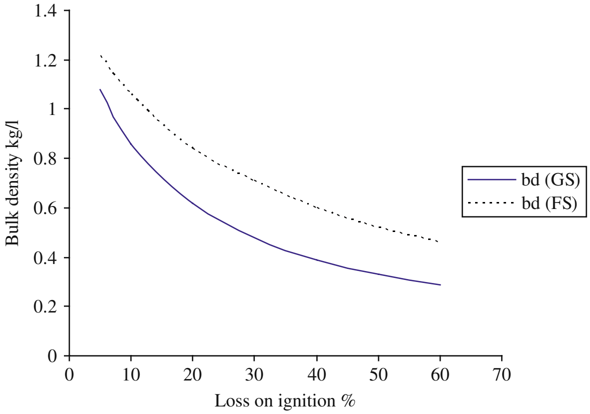

Fig. 2.4 Relationship between the % loss on ignition and the bulk density as found for the data in Table 2.1 for greenhouse soils (GS) in comparison with the relationship found for agriculture field soils (FS) by Kortleven (1970)

For field soils:

$$\rho = \frac{1}{2.52 f_I + 0.65} \tag{2.11}$$

In which:

ρ = bulk density in kg l^{-1}
f_I = mass fraction loss on ignition

The lower bulk density of the greenhouse soils includes a higher air volume.

In the foregoing formula organic matter contents and loss on ignition were not distinguished. Mostly, there are no significant differences between both characteristics. The fraction loss on ignition can be somewhat higher than the fraction organic matter, due to loss of adsorbed and structural water and the loss of CO_2 from carbonate. In a research with 75 samples of greenhouse soils Van den Ende (1988b) presented following relationship:

$$f_I = 1.013 f_H + 0.019 \tag{2.12}$$

In which:

f_I = mass fraction of loss on ignition
f_H = mass fraction organic matter

The differences between both characteristics are small and not important for practical use. Mostly the loss on ignition will be used, because of an easier determination method.

The role of organic matter in greenhouse soils is different. Next to the effect on the soil structure, it plays an important role in the water holding capacity of soils. In different researches a close relationship was found between the fraction loss on ignition and the water content of greenhouse soils. Van den Ende (1988a) and Sonneveld et al. (1990) presented comparable functions for this relationship, as will be shown in Section 3.3. The functions presented are operative for soils containing well decomposed organic matter. Soils with less decomposed organic matter will contain much more water in relation to the fraction organic matter, as found with the peat material used for substrate preparation (Kipp et al., 2000). In former time, when the irrigation was laborious and not frequently carried out, the water holding capacity of soil was an important characteristic. With the modern irrigation techniques in greenhouses it is of secondary importance. The same is true for the cation adsorption capacity of organic matter, which is less important due to the frequent top dressings with the modern fertigation techniques.

Besides the organic matter content the clay content is also important with respect to the water holding capacity of soils. However, the effect is less than those of the organic matter as is clear from formula (2.13), (Van den Ende, 1988b).

$$W_f = 2.374 f_H + 0.376 f_C + 0.134 \tag{2.13}$$

In which:

W_f= the mass ration water/solid phase
f_H= mass fraction organic matter of oven dry soil
f_C= mass fraction clay of oven dry soil

From the formula it is clear that the effect of organic matter on the water holding capacity is about six times higher than those of clay.

Organic matter in soils, even the well decomposed form, gradually decomposes and some of the residual products of this process become soluble in the soil solution. These organic complexes can strongly affect the availability and the uptake of some micro nutrients. This maybe is one of the reasons that there is such a poor correlation between the results of water soluble micronutrients in soil solution and plant tissues. The soluble organic components in the soil solution can surely affect the availability (Marschner et al., 1987; Verloo, 1980). See also results presented in Section 10.8.

2.3.2 Soil Improvers

Soil improvers are widely used in greenhouse cultures to stabilize or increase the organic matter content of soils. Therefore, the organic matter is the main constituent of soil improvers. Besides an increased water holding capacity and cation exchange capacity, most soils show an improved structure by the addition of organic matter. The latter, especially is the case with clayey soil types, but also on loamy soils such effects can be expected. On sandy soils the addition of organic matter is merely important for an improved water holding capacity and an improved cation adsorption capacity. With heavy additions of organic matter, especially the more stable compounds like peaty materials, the organic matter content of sandy soils can become too high, with as consequence that the space between the aggregates are filled with organic matter, which hinders the vertical transport of water. Such effects can occur with sandy soils when organic matter contents increases over 10%. Therefore, it is recommended to increase the organic matter content on sandy soils not above 5%, being the optimum level for such soils. For some root crops, like radish and carrots, soils with low organic matter content are preferred. Such root crops grow best on pure sandy soils as they show an increased root branching with high organic matter contents, which is not appreciated and considered as a negative quality characteristic.

Soil improvers can be applied by mixing through the soils as well as by mulching. This depends on the crop, the soil type and the soil improver used. Generally, it is not recommendable to place an organic soil improver deep into the soil, where the penetration of air is difficult. This especially counts for soil improvers containing fresh organic material and for heavy soils with a poor penetration of air into deeper soil layers, like with soils with high clay contents. For an optimum decomposing process sufficient oxygen should be available, which always cannot be ensured in deeper soil layers.

Soil improvers frequently used in greenhouses are listed in Table 2.9. Beside the organic matter soil improvers often contain substantial quantities of mineral nutrients. Some soil improvers contain much residual salts, which can be a drawback. With the use of such soil improvers the osmotic potential of the soil solution can markedly be decreased which can require extra water supply to wash out the residual salts from the root zone. Only the most common types of soil improvers are mentioned. The contents of organic matter and mineral elements vary strongly, because of origin, preparation method and storage conditions. The data as listed in Table 2.9 are derived by comparison of the data of different authors,

Table 2.9 Composition of soil improvers used in greenhouse industry. The data roughly reflect the composition got by comparison of the data of authors mentioned at the bottom of the table. The data are expressed in kg dry matter, organic matter and total N, P and K supplied with 1000 kg fresh soil improver

Type	Dry matter	Organic matter	N	P	K
Farmyard manure	250	120	5.5	2	7
Cattle slurry	80	50	5.5	1.5	4.5
Chicken manure	600	400	26	11	18
Spent mushroom compost	350	180	7	2	8
Green compost	650	150	7	1.5	5.5
Peat	500	450	5	0	0
Bark	400	300	3	0.5	2

The data in this table are derived by comparison of data published by: Bokhorst (2005a and b); LNV (undated); Raviv et al. (2002); RHP (2008); Solbra (1979); Voogt (2008); Van der Wees (1993).

as is made clear at the bottom of this table and the differences found among the results of these authors learned that a variation of 50% will be taken into account. The water content with which the soil improver is delivered is a main characteristic, because it determines strongly the contents of valuable constituents by weight. High water contents suppress these contents on the fresh materials. The addition of soil improvers can be based on a quantity of dry matter. The constituents as expressed on the fresh material can be converted to contents based on dry material following formula (2.14).

$$C_D = \frac{C_F}{f_D} \tag{2.14}$$

In which

C_D= constituent expressed on dry matter
C_F= constituent expressed on fresh material
f_D= mass fraction dry matter

The water contents vary strongly among the types, but also within the type great variations occur. Cattle slurries easily has mass fraction of water higher than 0.95. Peat, chicken manure and compost easily have a mass fraction of water below 0.50, but in wet condition this quickly increases up to 0.75. The varying water content of solid soil improvers strongly affects the advisable quantity when based on fresh mass, since the water content usually is not always available at the moment of application. Addition on volume basis will affect the advisable quantity less than application on mass basis, because the water content of solid soil improvers scarcely affects the quantities of essential constituents in a volume. However, this is not in force for liquid manures. Application on volume basis requires a good definition of bulk density. Such a definition is developed by a European regulation (CEN, 2000, 2007). Last decennia the application of soil improvers is seriously embedded by governmental regulations, which restricts the application of soil improvers by limits for maximum additions. These limitations are on the one hand determined by the content of heavy metals, related to the maximum acceptable yearly additions of these metals as established for sewage sludge and composts (LNV, undated). On the other hand, the application is limited by regulations for maximum acceptable additions of N and P, as will be discussed in Section 16.6.

In history an application of 70–100 $m^3\ ha^{-1}$ farmyard manure or green compost every year or every second year was a normal practice to keep the soil structure of greenhouse soils in a good condition. The quantities applied nowadays are more focussed on the possibilities within the regulations. There is a great variation in the composition among the deliveries of soil improvers. Therefore a secure application within the limits set, often requires a chemical analysis of each delivery of a soil improver. This for example is nowadays obligatory within Dutch regulations.

The K and the P added with the soil improver should be directly taken into account on the total nutrient requirements. For P this usually solely concerns the base dressing, because this element is exclusively added as such. However, often the P required as base dressing is less than the quantity applied by some soil improvers, like animal manures and composts. Thus, applications of soil improvers can lead to accumulation of P in greenhouse soils, when the limits set are crossed. The addition of K with the soil improver directly affects the base dressing, but can work on the top dressing as well. Many soil improvers contain limited readily available N and thus, additional base dressing with N fertilizer is mostly required. Not available N is released during the decomposition process and possibly will be taken into account with the top dressings.

The organic N and P compounds in manures become available to plants with the decomposition of the organic matter in it by the micro biological activity in the soil. The rate of decomposition of the organic matter and henceforth the availability of N and P from the manures depends much on the characteristics of the soil improver (Sluijsmans and Kolenbrander, 1977), like the C:N ratio in particular. Besides, also the soil type and the growing conditions are important. In greenhouses the soil temperature, the moisture content and the porosity of the soil are mostly optimal for a quick decomposing process. Therefore, the decomposition in greenhouses will be faster in comparison with field conditions. For the calculation of the mineralization dynamics of organic matter, the simple and easy to handle one-dimensional model of Janssen (1984) proved to be useful. In this model the variation in the decomposition rate of all constituents of a soil improver is reduced to a single parameter, being the "initial age" of the material. The N mineralization calculated by this model is in good agreement with the results of incubation tests and field experiments (Marcelis et al., 2003). Thus, the N release of manures in time can be estimated with this model. With application of soil improvers with fresh organic material, specifically material with a high C:N ratio, temporal immobilization of mineral N is possible and addition of extra N by fertilizers with the base dressing can be necessary. The mineral N absorbed in advance will become available during the decomposition process.

The organic matter in different peat types has a relatively high stability, especially the black, well decomposed types. Such types of peat need to be well frozen in wet condition in the field before drying to ensure that it is suitable as a soil improver. Insufficient frozen black peat does not sufficiently absorb water after drying out and these properties are irreversible.

2.3.3 Contamination

In the commercial intercourse of soil improvers a great variation of waste products are available. The use of products from which the origin is not clear is not advisable. Ingredients of waste products from industries may be toxic to people or to plants. Even when these are not directly toxic to plants, the addition to soil can include problems in future. When for example waste products contain high contents of heavy metals, concentrations in soils can accumulate to undesirable levels by regular additions during years. This often does not directly affect plant growth, but the uptake of heavy metals by plants can increase to an unacceptable level in the produce for human consumption. Therefore, governmental regulations have set strict maximum limits for the contents of heavy metals in soil improvers. This especially is the case for different compost types, because it is well known that this material sometimes contains high concentrations heavy metals. The occurrence of these contaminants in composts differs strongly and depends much on the character of the waste left by local industries. Products like sewage sludge and municipal waste compost are well known as materials often contaminated and therefore, are not recommended as a soil improver in greenhouses. Bio waste composts and green composts commonly contain acceptable concentrations of heavy metals and are mostly suitable as a soil improver for greenhouse soils. However, the concentrations will be determined and are bound on limits. A review of the limits as has been set in the regulations within the different countries of the European Community is listed in Table 2.10 (Amlinger et al., 2004). The limits show great differences among countries. In the countries out of the European Union, like the USA, also limits are formulated, but these are often much higher than those within the European Community. The values for compost from bio waste as formulated within the European Community for organic production (EC Regulation, 1991) are added in the last column of Table 2.10. Manure and slurry from animal origin has sufficient low concentrations of most heavy metals. However, in some materials often high Cu and Zn concentrations can be determined, especially those derived from pig farms (CEN, 2004).

The application of soil improvers in relation to environmental consequences for soil grown crops and the use as a constituent for substrates will be discussed further on in the Chapters 16 and 11, respectively.

Table 2.10 Limits and mean values for total concentrations of heavy metals in green compost and bio waste compost within the European Community and values for compost as proposed for compost from bio waste (Amlinger et al., 2004). The concentrations are expressed as μmol kg^{-1} and as mg kg^{-1} dry matter

	Limit values within EuC countries						EuC organic growing[2]	
	Minimum		Maximum[1]		Mean[1]			
Elements	μmol	mg	μmol	mg	μmol	mg	μmol	mg
Cd	6.2	0.7	26.7	3.0	12.5	1.4	6.2	0.7
Cr	962	50	4808	250	1788	93	1346	70
Cu	393	25	9434	600	2248	143	1101	70
Hg	1.0	0.2	15.0	3.0	5.0	1.0	2.0	0.4
Ni	170	10	1704	100	801	47	426	25
Pb	217	45	1351	280	584	121	217	45
Zn	1147	75	22936	1500	6361	416	3058	200
As	67	5	668	50	307	23	–.–	–.–

[1] Some exceptional high values excluded;
[2] as proposed for compost from bio waste.

Chapter 3
Soil Solution

3.1 Introduction

The characteristics of the soil solution in the root environment in the greenhouse industry differ much from those for field grown crops. This is caused firstly by the growing conditions in the greenhouse, which strongly differ from those in the field and secondly the function attributed to the soil solution with respect to plant development. One of the most striking differences between growing in the greenhouse and in the field is the exclusion of the natural precipitation in greenhouses, which offers opportunities for a full control of the water supply. Another difference is the heavy fertilizer application, related to the high nutrient uptake. In addition these application fertilizers are for the greater part added by fertigation. Furthermore, the irrigation and fertilizer addition not only has a function with respect to supply the plant with sufficient nutrients and water, but in greenhouses these actions are also a tool to control plant growth and produce quality. Sometimes, low osmotic potentials in the soil solution are maintained to prevent a lush growth or to improve fruit quality. Such effects on plant development, especially makes sense in substrate growing, where plants are grown in small rooting volumes and thus the composition of the soil (substrate) solution easily can be adjusted, for example on the demand of the crop under changing growing conditions. Thus, in principle it seems possible to supply plants under greenhouse conditions at the right time with the right quantity of water and nutrients, and losses of water and nutrients to the environment can be minimized. However, this is often frustrated by a heterogeneous water supply of irrigation systems, a heterogeneous water uptake by plants and accumulation of salts in the root environment from the irrigation water used. Thus, a precise matching on the demand by the water supply is hindered by an overdose of irrigation water to equalize the differences between wet and dry spots and to prevent too high accumulations of residual salts.

In the greenhouse industry an adequate management of water and nutrient supply is important. On the one hand to maintain optimal conditions for the plant in the soil solution with respect to plant nutrient uptake and to the requirements for the osmotic potential and on the other hand with respect to prevent leaching of nutrients and by this prevention of environmental pollution. Especially the high concentrations of nutrients in the soil solution contribute strongly to a high environmental pollution

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per area. This does not mean that the leaching of nutrients is high in relation to the total uptake. However, this item will be discussed further on in Chapter 6.

In the present chapter the osmotic potential of the soil solution will be discussed in relation to the prevailing moisture conditions during cultivation. Hereby, the connection will be discussed between the definition of the soil solution of soils in situ and those of substrates, because in the greenhouse industry substrate growing is important and will expand further on. Following the definition for soil solution the term "substrate" solution will be defined, being the solution extracted from substrates at moisture contents maintained during crop cultivation. Besides the osmotic potential, being a measure for the total of the different concentrations of mineral constituents, an impression will be given of the specific composition of the mineral constituents in the soil solution. Finally some guidelines about the role of the composition of the soil solution in relation to the mineral uptake of crops are presented.

3.2 Osmotic Potentials of Soil Solutions

In Table 3.1 the composition of soil solutions from field soils is given in comparison with those from greenhouse industry. In the comparison soil solutions as well as substrate solutions are taken into account. The most striking difference between the solutions derived from fields soils and those from greenhouses soils are the overall much higher nutrient concentrations in solutions from greenhouse. This especially holds for greenhouse soils where the EC in the solution is highest. Furthermore, it is obvious that in greenhouse cultivation nutrients contribute substantially to the total salt concentrations of soil and substrate solutions and thus to the osmotic potential.

Table 3.1 Ionic compositions of soil solutions. Ions expressed as mmol l^{-1} and EC as dS m^{-1}. The no's 1–5 are from field soils and the no's 6–9 from greenhouses

No[1]	K	Na	NH_4	Ca	Mg	NO_3	Cl	SO_4	HCO_3	P	EC
1	1.7	5.4	–	8.9	3.7	9.1	8.4	1.6	0.8	0.02	–
2	0.3	0.2	–	2.2	0.6	3.7	2.1	0.2	–	–	0.6
3	0.5	0.3	0.05	1.6	0.5	3.2	2.4	0.6	–	0.02	–
4	0.1	–	0.03	1.1	0.0	0.6	–	–	–	0.01	–
5	0.2	–	1.10	5.3	0.1	12.3	–	–	–	0.01	–
6	6.6	13.2	0.39	22.3	8.7	24.1	15.0	19.1	–	0.32	6.5
7	4.6	1.8	1.2	4.2	3.2	11.4	1.3	3.2	–	1.7	2.3
8	8.0	–	<0.5	10.0	4.5	23.0	–	6.8	–	1.0	4.0
9	5.0	–	<0.5	5.0	3.0	12.5	–	3.0	–	0.9	2.2

[1] Composition derived from: 1 – means of a historical series from Adams (1974); 2 – means of data of Qian and Wolt (1990); 3 – means of data of Peters (1990); 4 and 5 – data of Barraclough (1989) before and after top dressing with N, respectively; 6 – means of greenhouse soils by Van den Ende (1989) and Sonneveld et al. (1990); 7 – means peaty substrates of Sonneveld and Van Elderen (1994); 8 and 9 – recommended values for rock wool grown tomato and rose, respectively (Sonneveld, 1995).

This especially is the case in substrate systems where low saline primary water is used, and the osmotic potential is thus more or less solely brought about by nutrients. However, when water is used with a higher salinity level, and low osmotic potentials are desired in substrate cultivation, as indicated in Table 3.1 for tomato, the nutrient levels will be reduced to the required optimum for plant nutrition, while the osmotic potential will be lowerd further by accumulation of the residual salts from the saline water (Sonneveld, 1995). In the Chapters 7, 13 and 16 this item will be discussed in detail.

The most important characteristic of the soil solution for greenhouse cultivation is the determination of the EC, because the results of this determination in soil solutions is within the operational range for greenhouse cultivation closely linearly correlated with the osmotic potential of the soil solutions. Such a close relationship will be found, when the osmotic potential is solely build up by ions and ionic pairs of mineral salts. The relationship between the EC and the salt concentration is linear, over a relatively wide range. True enough, each ion has its own specific contribution to the EC (McNeal, et al., 1979; Sonneveld et al., 1966). In Fig. 3.1an impression is given of the relationships between the concentrations of different salts and the EC of a number of single salt solutions as found by Sonneveld et al. (1966). The contribution of a specific salt to the EC depends on factors like the valence of the ions, the dissociation constant, the activity of the ions and the ion pair formation and furthermore the temperature of the solution. In Fig. 3.1 the linear relationships between the salt concentrations and EC values of different single salt solutions are shown over a range up to 60 and 90 mmol l^{-1} for tertiary and binary salts, respectively. The

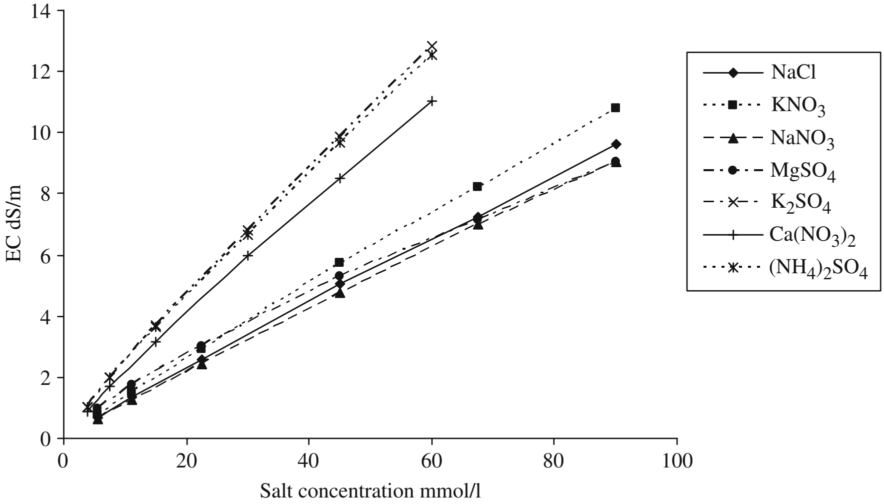

Fig. 3.1 The relationship between the concentrations of different salts and the EC, after Sonneveld et al. (1966) (Relationships calculated: NaCl, EC = 0.106c + 0.17; KNO_3, EC = 0119c + 0.24; $NaNO_3$, EC = 0.100c + 0.18; $MgSO_4$, EC= 0.094c + 0.73; $Ca(NO_3)_2$, EC = 0.180c + 0.39; K_2SO_4, EC = 0.208c + 0.45; $(NH_4)_2SO_4$, EC= 0.204c + 0.44)

relationships between salts differ strongly. With increasing solution temperature the EC of salt solutions increases also. Therefore, the EC is expressed at a standardised temperature, mostly 25°C. When the EC is measured at a different temperature, the value at the standard temperature can be approached by the temperature coefficient, which is the relative increase or decrease of the EC by an increase or decrease of 1°C, respectively. This coefficient is somewhat different for the temperature interval, the relation temperature and the salt composition of the solution. However, at a relation temperature of 25°C and no bigger deviations than 10°C a temperature coefficient of 2% is proved to be very suitable (Campbell et al., 1948; Sonneveld et al., 1966). Modern apparatus compensate the effect of the temperature deviation automatically.

For mixed salt solutions McNeal, et al. (1979) showed a linear segment method with which the contribution of various concentrations of different salts to the EC can be calculated. The method is suitable for concentrations up to 50 mmol l^{-1} for mono-valence and up to 25 mmol l^{-1} for bi-valence ions. The low intercepts given with these linear relationships point out that they are suitable for calculations until rather low concentrations.

For rough estimations the formula given by Sonneveld et al. (1999) can be used for mixed salt solutions.

$$EC \approx 0.1C^{+} \tag{3.1}$$

In which

EC = electrical conductivity of the solution in dS m^{-1}
C^{+} = the sum of valences of the cations in mmol l^{-1}

However, for a precise calculation of the EC from the ion composition the already mentioned method presented by McNeal et al. (1979) will be recommended.

For soil solutions, but also for various other mixed salt solutions like soil extracts, and natural waters a close relationship has been found between the osmotic potential and the EC, as shown with the data in Fig. 3.2. The relationships found for different solutions show strong similarity and a general formulation can be established as given in Eq. (3.2).

$$OP \approx -33.3EC \tag{3.2}$$

In which

OP = osmotic potential of the solution in kPa at 0°C
EC = electrical conductivity of the solution in dS m^{-1} at 25°C

For strongly diluted extracts like the 1:5 by weight soil extract, a somewhat different relationship has been found. The data agree very well with the results presented by Campbell et al. (1948).

The osmotic potential of the solution in the root environment in greenhouse cultivation appeared to be an important factor for growth regulation of crops. This was

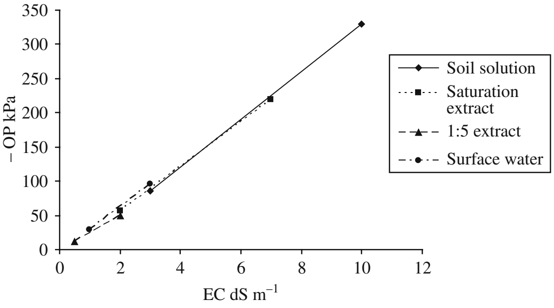

Fig. 3.2 The relationship between the EC and the osmotic potential (OP) of different solutions, after Van den Ende (1968) and Sonneveld and Van den Ende (1967). The *dots* show the interval of the data (Regression equations: Soil solution OP = –34.9 EC – 19; Saturation extract OP = –32.6 EC – 8; 1:5 extract OP = –24.5 EC – 0; surface water OP = –33.3 EC – 4)

not recognised from the beginning. In history, low osmotic potentials (high EC) in greenhouse soils were exclusively connected with the negative aspects of high salinity, like growth reduction and nutrient disorders (Riemens, 1951; Van den Ende, 1952). However, in greenhouses where crops easily show a lush growth often connected with a poor quality, also positive effects of a low osmotic potential in the soil solution were observed (Van den Ende, 1955). The lush growth of crops under greenhouse conditions especially appears at relatively high temperatures, reduced light intensity and ample water supply. Such conditions for example occur predominantly in winter in North-West Europe. Gradually, the osmotic potential of the soil solution became a tool for greenhouse growers to manipulate crop development. The cultivation in substrate as developed for various greenhouse crops especially enhanced the availability of water in the root environment by the usually low matrix potential in the substrates of such growing systems, which accentuate the need for the use of the osmotic potential as a tool for growth regulation. Substrate growing, as mentioned before, offers excellent perspectives for such a regulation, because of the controlability of the usually small rooting volumes.

In greenhouse crops disorders of a high osmotic potential (low EC) in the root environment are well known in vegetables as well as in flowers and covers a great variation of plant characteristics. Examples are: irregular colouring of tomato fruits (Sonneveld and Voogt, 1990), glassiness in lettuce (Maaswinkel and Welles, 1986) and aggravation of the occurrence of soft rot in Hippeastrum bulbs (Van den Bos, 1996). Guide values for required and acceptable concentrations of nutrients and residual ions in the root environment will be discussed in Chapter 7.

3.3 Moisture Contents

A drawback with the determinations in soil and substrate solutions is the lack of a good definition of the moisture status of soils and substrates for preparation of the solution. The moisture content of a soil fluctuates with the evaporation and the water uptake of the crops grown and the precipitation, irrigation and capillary rise.

This especially occurs for field crops grown without artificial irrigation or with low frequency irrigation schedules. In such cases, the moisture withdraw from the root zone between irrigations can be considerable, which for example directly will be reflected by a decrease of the osmotic potential of the soil solution. The fluctuations in greenhouse soils are restricted, because of the high frequency irrigation schedules maintained. This especially is the case in substrate systems, where the irrigation frequency under high transpiration conditions increases up to several times per hour.

3.3.1 Greenhouse Soils In Situ

For a wide range of soil types Van den Ende (1988a) found a close linear relationship between the water content of greenhouse soils cultivated with tomatoes and the water content at a pressure head of –6.3 kPa, as shown with formula (3.3).

$$w_f = 1.047 w_{-6.3} - 0.012 \quad r = 0.987 \tag{3.3}$$

In which:

$w_f =$ mass ratio water/solid phase of field moist soil
$w_{-6.3} =$ mass ratio water/solid phase of soil at a pressure head of – 6.3 kPa

Thus, the water contents of the greenhouse soils grown with tomato were more or less equal to that at a pressure head of – 6.3 kPa.

Furthermore Van den Ende (1988b) found that the water content of the field moist soil was closely related to the loss on ignition, as given in following formula.

$$w_f = 2.617 f_l - 0.118 \quad r = 0.985 \tag{3.4}$$

In which:

$w_f =$ mass ratio water/solid phase of field moist soil
$f_l =$ mass fraction loss-on-ignition of oven dry soil

Sonneveld et al. (1990) also determined the relationship between the loss on ignition and the water content under growing conditions and found a comparable relationship for a series of 75 greenhouse soil samples. These samples were gathered from greenhouses with different crops, merely during the cultivation period. The mass fraction organic matter and clay of the soils varied from 0.03–0.61 and 0.03–0.40, respectively. The relationship is shown in Fig. 3.3, and the equation found is given in formula (3.5).

$$w_f = 2.821 f_l - 0.100 \quad r = 0.982 \tag{3.5}$$

Both formulae resulted in comparable values over a wide range of soil types. Thus, on basis of these formulae the field moist condition for greenhouse soils can be defined.

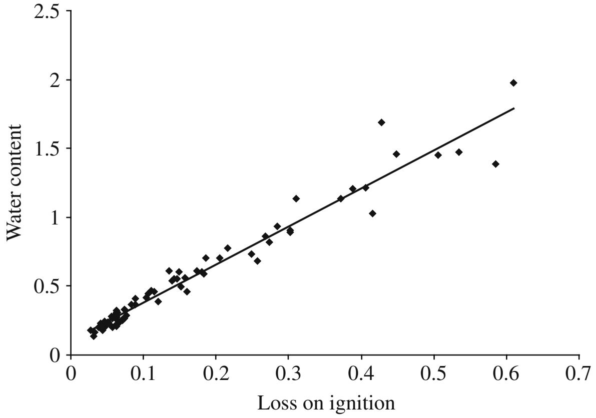

Fig. 3.3 The relationship between the loss on ignition (m/m) of greenhouse soils and the water content (g/g) at field moist conditions. After Sonneveld et. al. (1990). Regression equation: $y = 2.821x + 0.100$, $r = 0.982$

With the given formulae also the water volume can be calculated because the bulk density is also closely related with the loss-on-ignition fraction (Sonneveld, 1990), like already given in formula (2.10).

Combination of the formula (3.5) and (2.10) gives an equation for the water volume in greenhouse soils, as shown in Eq. (3.6).

$$wv_f = \frac{2.821\, f_l + 0.100}{4.67\, f_l + 0.69} \tag{3.6}$$

In which

$wv_f =$ volume fraction of water of field moist soil
$f_l =$ mass fraction loss-on-ignition of oven dry soil

This formula can be used to calculate roughly the current moisture condition of greenhouse soils under growing conditions and will be used as a standard when reference is made to the soil solution of greenhouse soils. This definition is true with a reasonable frequent irrigation and thus, the relation between loss on ignition and water content are in agreement with the formula presented as (3.5).

3.3.2 Substrates

For substrates no reasonable relationship between organic matter and water holding capacity will be expected, due to the great variation of materials used as a substrate or used as a substrate constituent and utmost the great variation of the quality within these materials. For example, a lot of substrates do not contain noteworthy organic matter, while they have a high water holding capacity. But even when substrates contain considerable quantities organic matter, like peaty substrates, the characteristics of the organic matter differ strongly and show a great variation in water holding capacity. In an investigation with peaty substrates (Sonneveld et al., 1974) a correlation coefficient of 0.809 was found between the mass fraction loss-on-ignition and the ratio moisture/solid phase at a pressure head of –3.2 kPa, which is considerably lower than the correlation coefficient found with greenhouse soils. Since then the variation in materials used to produce substrates is strongly increased. The pressure head of –3.2 kPa was chosen as being approximately the moisture content under growing conditions in that period. Later on, the moisture contents of substrates during cultivation became higher.

The growing conditions are another hindrance for a precise estimation of the water holding capacity. The moisture in most substrates is quite loosely bound and thus, the thickness of the substrate layer applied in the growing system will affect strongly the water holding capacity. Another factor is the irrigation method that plays an important role. When the water is supplied on the top, the water distribution in the substrate will differ strongly from the situation with water supply from the bottom. Thus, the definition of the water content at field capacity of a substrate not only depends on the characteristics of the substrate, but also on the growing conditions.

Wever (1995) compared the bulk densities and the water contents of a series of peaty growing media as found in practice for potted plants with the same characteristics measured at the laboratory following the CEN standard methods (CEN, 2006). The water content in the samples prepared at the laboratory following this method was measured at a pressure head of –1 kPa. The correlation coefficient between the bulk density as found in the field and measured at the laboratory was rather low (r = 0.83), but the average values had an acceptable agreement. The correlation coefficient for the water content found under field conditions and the content determined at –1 kPa at the laboratory was also rather low (r = 0.83), but on average the contents determined at the laboratory approached the field condition reasonably. Results of some calculations are listed in Table 3.2. The data in this table show that for a wide range of peaty substrates with a bulk density in the range from 50 to 300 kg m^3, that there is on average an acceptable agreement between the water contents of the growing media under field conditions and those found at the laboratory at –1 kPa. Thus, under growing conditions the water contents of the peaty growing

Table 3.2 Bulk density and water content of peaty substrates as determined at the laboratory at –1 kPa and comparable values of the bulk density and water content under field conditions, estimated by the regression equations found by Wever (1995)

Bulk density kg m^{-3}		Water content g g^{-1}	
Determined	Value estimated for practice	Determined	Value estimated for practice
50	54	10	9.6
300	261	3	3.9

media approaches on average reasonably the water contents at a pressure head of –1 kPa. The low correlation coefficient found for the relationships can be explained easily by the strong differences realised under growing conditions, as there are the different potting techniques, irrigation methods and frequencies, differences in time between latest watering and sampling errors and so on.

For some substrates other than peat, the water content at a pressure head of –1 kPa is not a good estimation of the water content under growing conditions. These substrates have lost already important parts of the water at such a relatively low suction. It seems that for these substrates the water content at free drainage after saturation is a better estimation for the water content under growing condition than at a pressure head of –1 kPa. For bulk material this free drainage situation can be compared with the determination of the water content at –0.3 kPa at the laboratory, being half of the height of the rings used for the standard method of CEN (2006). For pre-shaped material half of the height of the slabs or blocks should be considered as the pressure head of the free drainage condition. In Table 3.3 the water contents of a number of substrates is given at free drainage (leak out) condition and at –1 kPa, following Kipp et al. (2000). In mostly cases there is a considerable difference between both water contents. For pre-shaped materials like slabs and blocks of PU-foam and rock wool it should be concluded that the water content under growing conditions will be approached mostly better by the "leak out" condition than at –1 kPa, because at this pressure head an important part of the water is lost and the "leak out" condition approaches the situation in the field. The water content of expanded clay granules is already low at the "leak out" situation. Under growing conditions this substrate is usually placed in a water layer, which layer plays an important role in the uptake of water and nutrients. For the bulk materials the thickness of the substrate layer especially determines the water content at field capacity and thus at what pressure head the determination on the laboratory should be carried out.

Table 3.3 Relative water contents by volume of a series of substrates at a pressure head of –0.3 (leak out) and –1 kPa

	Pressure head	
Type of substrate	–0.3 kPa[1]	–1 kPa
Wood fibre	0.72	0.32
Expanded clay granules	0.19	0.13
Coco peaces	0.40	0.33
Coco dust	0.91	0.67
Perlite	0.44	0.31
PU foam slabs	0.60	0.06
PU foam pieces	0.58	0.07
Pumice	0.58	0.40
Rock wool slabs	0.94	0.42
Peat	Nd	0.79

[1] For bulk substrates, for pre-shaped substrates the pressure head will be half the height of the slabs.

After Kipp et al. (2000).

So with respect to a definition for “soil solution” following general conclusions are possible:

- For substrates retaining their water at a pressure head of –1 kPa or higher, the water content at –1 kPa should be considered as being the field capacity
- For substrates that have lost an important part of their water at –1 kPa, the water content at free drainage after saturation should be considered as being field capacity, because such substrates will be used in thin layers
- For very course substrates with a low water holding capacity placed in a water layer, this water layer at the bottom should be considered as being the “soil solution”.
- For growing systems with a very restricted substrate volume and a high speed of the nutrient solution, like NFT and deep water culture, the circulating water can be considered as the “soil solution”.
- For strongly different growing systems and growing conditions strongly different from the formulations described, specific definitions are required and should be formulated.

3.4 Changes in the Chemical Composition

The chemical composition of soil solutions will change strongly, mainly by factors like nutrient uptake by crops, leaching of nutrients by irrigation and supply of nutrients by fertilization. The grower often switches the concentrations of specific ions as well as the total ion concentration (EC) deliberating the requirements of the crop. For some crops the EC is increased strongly like at the start of fruit vegetable crops to promote an early fruit setting and to prevent a lush growth, as mentioned in Section 3.2. Such an increase is realised by use of accumulated residual salts in the soil left from the former crop cultivation, by the addition of extra nutrients, or by a combination of both factors. Later on in the growing cycle of such crops, when lower EC levels are required, the grower let them gradually decrease by means of over irrigation and by the nutrient uptake of the crop. When necessary, growers start the fertigation to prevent that the nutrient concentrations will be decreased until too low values, which negatively can affect fruit quality. In Fig. 3.4 the course of the cation composition of the soil solution is shown for the described situation, with a soil grown tomato cropping as an example. The cations were determined in the saturation extract, the concentrations of which are closely correlated to those in the soil solution. The NH_4 concentration is high at start, because of the steam sterilisation carried out just before the first sampling (see Chapter 10). The concentration gradually decreases with increasing microbiological activity in the soil. The concentrations of K, Ca and Mg were brought on the required high levels for tomato by base dressing. During the first months the concentrations of these cations gradually increase further on, by evaporation and action of capillary rise from the saturated zone, as long as there was no irrigation.

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