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Review Article

Environmentally sound plant production by means of soilless cultivation

Rolf Udo Roeber

Research Station for Horticulture, Weihenstephan-Triesdorf University of Applied Sciences, D-85350 Freising, Germany
e-mail: rolf.roeber@hswt.de; jrundrr@t-online.de

Abstract

German and European authorities were looking for possibilities of a reduced use of agrochemicals. Among these, fertilizers play an important role, because their nitrogen can be leached out and percolate into the underground water. Thin layer cultivation of cut flowers and vegetables has been introduced since about 20 years. This system contains a horticultural substrate and a plastic foil underneath, which separates the subsoil from the cultivation zone. So, leaching should not be possible. The provision with water can be regulated by tensiometers and the nutrients are added in the amounts wanted, so that fertilizer and water can be saved efficiently. A lot of different materials may be used as substrates. This system is to be run recirculating and hydroponically as well. The fertilization of the plants in the systems described can take place by the application of different amounts of fertilizers. The fertilizers used are either single salts or composed. The pH-value in a recirculating nutrient solution can be regulated by the use of different nitrogen forms. On the other hand, the fertilizers must be applied in plant tolerable concentrations, which represents about 0.5 to 1.5 g L^{-1} of water. There is evidence, that all systems can lose gaseous nitrogen. They need to be carried out with less water quantities but higher water quality than systems with cultivation in horticultural soils in situ. Furthermore, recirculating systems are to be used for cultivation of cut flowers and pot plants as well. In principle, two different systems are available, one with irrigation from above (drain water reuse) and the other from underneath (subirrigation).

Keywords: environment, hydroponics, irrigation, leaching, nitrogen, soils, substrates, water

Produção de plantas ambientalmente segura por meio de cultivo sem solo

Resumo

Autoridades alemãs e européias buscavam possibilidades para o uso reduzido de agroquímicos. Dentre elas, os fertilizantes exercem função importante porque o nitrogênio pode ser lixiviado e percolado para a água subterrânea. Uma estreita camada cultivada com flores de corte e vegetais vem sendo incrementada há 20 anos. Esse sistema contém um substrato hortícola e um plástico com papel alumínio na região inferior que separa o subsolo da zona de cultivo. Assim, a lixiviação não é possível. O fornecimento hídrico pode ser regulado por tensiômetros e os nutrientes adicionados em quantidades requeridas para que fertilizante e água sejam usados eficientemente. Grande quantidade de materiais pode ser usada como substrato. Esse sistema é para ser conduzido de forma recirculante e hidroponicamente. A adubação das plantas nos sistemas descritos pode ser realizada pela aplicação de diferentes quantitativos. Os fertilizantes usados são sais isolados ou compostos. O pH no sistema de solução nutritiva recirculante pode ser regulado pelas diferentes formas do nitrogênio. Por outro lado, os fertilizantes devem ser aplicados em concentrações toleráveis pelas plantas, o que corresponde a 0,5 a 1,5 g L^{-1} de água. Há evidências de que todos os sistemas podem perder nitrogênio gasoso. Os fertilizantes precisam ser conduzidos com menores quantitativos de água, mas em menores quantidades de água quando comparado com o cultivo em solos in situ. Além disso, os sistemas recirculantes devem ser usados para o cultivo de flores de corte bem como plantas em recipientes. Em princípio, dois diferentes sistemas encontram-se disponíveis, um com irrigação superficial (reuso de água drenada) e outro pela região inferior (subirrigação).

Palavras-chave: meio ambiente, hidroponia, irrigação, lixiviação, nitrogênio, solos, substratos, água

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Introduction

About 20 years ago the influence of increasing environmental awareness and more stringent laws resulted in a change of the techniques of fertilization in Germany and other European countries. The development of subirrigation systems with recirculation of water and nutrients led to more economical use of fertilizer and water in plant production. Therefore, the actual situation seems to be a lot less dramatic than described earlier by Molitor (1990). He had reported, for example, that in Germany the nitrogen (= N) content of greenhouse soils in some cases reached up to about 2000 kg ha^{-1} in the top layer to a depth of 100 cm.

The idea of practical application of recirculation goes back to Cooper (1979). He observed problems when cultivating in soils with very high salt contents, which could not be leached out due to the horizontal layers of the rocks under the subsoil. The reductions in the use of water, fertilizers and other agrochemicals are so large, that investments in environmental friendly systems are really highly profitable. Therefore, from an economical and ecological point of view the introduction and spread of these systems make lots of sense (Radlmayr, 1991). Furthermore, one should recognize the improved public image of plants produced under controlled environmental friendly conditions. In Switzerland gardeners were the first to be forced by a private distributor of horticultural products to cultivate plants under these conditions (Gysi, 1997). Meanwhile, in other European countries special systems of recirculation have been developed. On the other hand, the introduction of these special cultivation systems was necessary by the deterioration of the physico-chemical properties of the soils and their increased contamination with pests and diseases.

Definition

The run-off of water, nutrients, and other agrochemicals can be avoided by recirculating systems. These can be defined as systems, where the plants are cultivated outside the "natural" soil. Losses into the underground are minimized by adjusted addition of water and nutrients. The following types of systems are recognized:

pot plants	cut flowers, vegetables, mother plants
ebb-flow-systems	thin layers
gully-systems	hydroculture without substrate
hydroculture	hydroculture with substrate
Recirculation takes place in all pot plant systems and hydroculture. The systems keep the root zone closed only.	
after Roeber (1999)	

Two main groups of recirculating systems can be distinguished: those with (A) drain water reuse and those with (B) subirrigation. In principle, both systems can be used for the cultivation of plants (figure 1).

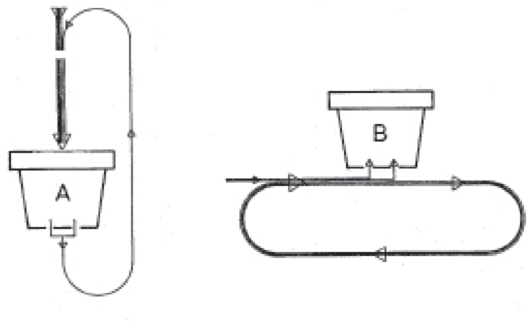


Figure 1. Recirculating cultivation systems (after Molitor, 1990)

Advantages and disadvantages of recirculating cultivation systems

The advantages of these systems firstly can be derived from the reasons of their introduction: ecology and economy. Furthermore, the requirement of water and nutrients of the plants must be satisfied periodically due to the fact, that the periodical demand of nutrients can differ tremendously as can seen in figure 2 (Sackmann & Lange (1980) cited by Leinfelder et al. (1990)).

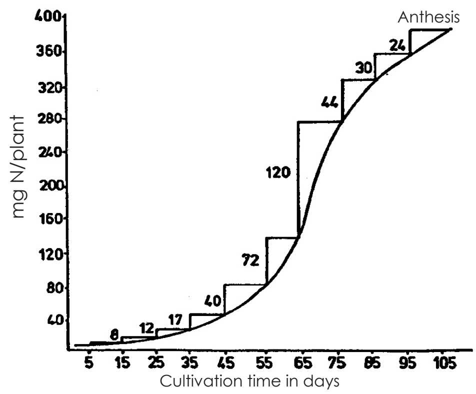


Figure 2. N uptake of cut Chrysanthemum x grandiflorum (ordinate: mg N/plant; abscissa: time in days; figures on the steps: mg N/10 days) during the cultivation period until anthesis

This requirement presupposes knowledge of the periodical demands of species and varieties, which is not always available.

The construction and supervision of the technical and computers installations make things more complicated and may result in more problems. Another disadvantage of recirculating systems may be the possibility of the spread of diseases and the built up of salts in the soil. This clearly has been demonstrated by Wohanka (1998), as can be seen from figure 3. Low risks can be observed with subirrigation (left) and high risks with drain water reuse (right).

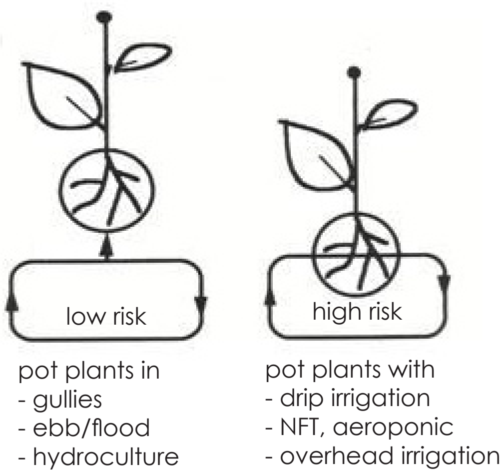


Figure 3. Risk of spread of diseases (after Wohanka, 1998)

Thin layer cultivation systems

Design of the system

The thin layer system must be set up on leveled ground (Leinfelder et al., 1990). To level the ground, the soil may be covered with about 2.0 cm of sand. The beds for plant cultivation will be constructed by covering the leveled ground with a 0.8 mm plastic film resisting temperatures of about 100 °C in case of steam sterilization of the substrate filled into the beds prepared (figure 4). The substrate used is placed onto the plastic material. The amount of substrate per m² depends on the length of the cultivation period and the size of the root system of the plants, e.g. for *Chrysanthemum* x *grandiflorum* 5.0 cm substrate depth is recommended and for varieties of *Alstroemeria* 20.0 cm (Leinfelder, 1993). Furthermore, the system is equipped with drip irrigation of about 15 orifices per m². The daily delivery of water or nutrient solution may reach up to 10 L m^{-2} day^{-1} or even more. The moisture of the substrate may be regulated by an analogous switch tensiometer. The pressure at the switch tensiometer should be set between -80 and -160 hPa, regulated by a computer, depending on plant species (Frenz, 1989). Plants, which are very sensitive to high moisture in the substrate, like *Euphorbia fulgens,* should always be kept very dry in the root zone, e.g. the tensiometer setting should reach -160 to -250 hPa or even more (Leinfelder, 1997).

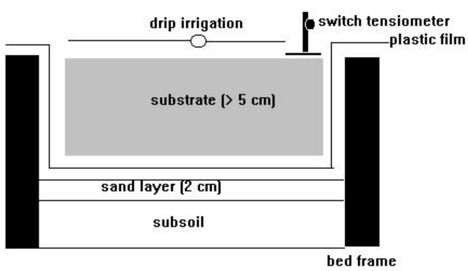


Figure 4. Design of a thin layer cultivation system

Problems can be observed, if the beds are not of even level, if the water or nutrient solution is not well distributed (reason: too few drippers per m²) inside the substrate or if the greenhouse roof is leaking and water from the outside interferes with the measurements of the tensiometers.

Substrates

In principle, nearly all types of substrate can be used in such systems. Substrates with an excellent horizontal distribution of the water, like peat moss or mixtures of peat and clay are preferred. Wood fibre based (< 40% vol. of the substrate amended with it) substrates are well suited for cultivation too (Leinfelder, 1993).

The amount of substrate per m² to be applied depends on the thickness of the layer. A layer of > 5 cm is always recommended for beginners. On the other hand, the amount of substrate can be reduced drastically to about 20 L m^{-2}, if special multicell units are used (Biermann, 1995; Eichin & Deiser, 1996).

Fertilization

The plants can either be fertilized on the basis of supply of certain quantities per unit of time, or by using certain concentrations of the nutrient solution, e.g. in the case of hydroponics.

Quantities of fertilizer

The amount of fertilizer to be added will come up to the same quantity as in the soil minus the losses by leaching into the subsoil. Furthermore, the amounts of fertilizer already added to the substrate must be taken into account, which depend on the thickness of the substrate layer. If the demand of nutrients per unit of time is known, the fertilizer can be added in small but adequate amounts. By the aid of computers the plants can be fertilized and watered according to special programs, but unfortunately our knowledge about the demand of the plant per m² and unit of time is still inadequate due to the fact, that the demand depends on several factors, e.g. time of the year (solar radiation), plant height, leaf area, and plant density (Grantzau & Scharpf, 1986).

So, the fertilization of plants in thin layers mainly may be carried out according to the concept of fertilizer concentration (Leinfelder et al., 1990).

Fertilizer concentration

The principle of the application of a certain fertilizer concentration has been proven in horticultural practice and also can be used in recirculating systems (hydroponics; see recirculating systems). The concentration of the nutrient solution applied depends on time of the year, solar radiation, and the growth stage of the plant. Furthermore, data from substrate analysis can be used for corrections (Leinfelder et al., 1990).

The standard concentration of the nutrient solution given to the plants can be derived from the calculation for the demand of water and nutrients, the nutrient concentration in the plants, and the transpiration of the plants. Quantities reach up to 0.7 to 1.0 g complete fertilizer (15% N in the fertilizer) per liter of water. In a first step it seems to be sufficient to adjust to the different demands of the plants for N and K by the choice of the respective complete fertilizer, e.g. 15:11:15 ($N:P_2O_5:K_2O$) or 15:7:22 or 15:5:25 or 20:5:10, all of them completed with Mg and micronutrients. An adjustment depending on the weather conditions is necessary, especially if extreme conditions last for an extended period. Due to the fact, that the consumption of water may depend mainly on solar radiation, a stable concentration of the nutrient solution applied leads to overfertilizing in periods of high light intensity and nutrient deficiency in periods of overcast skies or in the winter. Consequently, the following rules have to be considered:

A. Normal weather (50% cloudy): 100% of standard nutrient solution, e.g. 1.0g complete fertilizer per liter of water
B. Periods of seven days continuous sunshine (summer period): 60 to 70 % of standard nutrient solution, e.g. 0.6 to 0.7 g complete fertilizer per liter of water
C. Periods of seven days cloudy weather (winter period): 130 to 150% of standard nutrient solution, e.g. 1.3 to 1.5 g complete fertilizer per liter of water

The adaptation should last at least as long as the extreme weather conditions last. The regulation can be run by a computer.

The adjustment of fertilizer concentration to the stage of the plant growth may be done, if growth is retarded or has ended by the formation and development of flowers, e.g. *Chrysanthemum x grandiflorum*, *Euphorbia pulcherrima*, *E. fulgens*. In that case the concentration of the nutrient solution at the end of the growing period (last third of the whole period) can be reduced by 50% or even more.

Also, at the very beginning of the cultivation period, when the plants are young, the concentration 0.7 to 1.0 g fertilizer per liter of water may be used, if the nutrient contents of the substrate are in the optimum range (see table 1). If there is a great stock of nutrients in the substrate, the concentration of the nutrient solution has to be reduced in the early phase of the plant growth. Possibly, during this period plants need no nutrients, but water only. If starting with substrates low in available nutrients, the concentration of the nutrient solution has to be increased, because young plants transpire little water and therefore cannot take up sufficient nutrients. The reduction of the concentration of the nutrient solution at the end of the cultivation period can increase the quality of the plants. For the same reason the K-concentration of the nutrient solution may be raised.

Table 1. Optimum ranges of nutrients and salts for some ornamental plants with different nutrient demands (after Leinfelder et al., 1990)

nutrient demand or salt tolerance	low	medium	high
optimum ranges in the substrate (mg $\cdot L^{-1}$)			
N	50 - 150	75 - 200	100 - 250
P_2O_5	100 - 200	150 - 300	200 - 400
K_2O	75 - 150	100 - 250	150 - 350
Mg	50 - 100	75 - 150	100 - 200
salt (KCl)	500 -1000	1000 - 2000	1500 - 3000
examples	*Adiantum*, *Asparagus setaceus* (*A. plumosus*)	*Alstroemeria*, *Rosa*, *Bouvardia*, *Gerbera* poor growing, *Euphorbia fulgens*	cut *Chrysanthemum*, *Dianthus*, *Asparagus densiflorus* (*A. sprengeri*), *Gerbera* strong growing
Concentration of the nutrient solution (g $\cdot L^{-1}$)	0,7	0,85	1,0

From the viewpoint of simplicity, protection of the environment, possible trouble-shooting, the unknown demand of nutrients during the different growth stages, the high tolerance relating to the ratio of nutrients in the solution and its concentration, and the economic aspects (costs), the application of complete fertilizers with micronutrients instead of single fertilizers is emphatically recommended (Mewes et al., 1994).

A consequent and regular control and correction by substrate analysis seems to be useful, because there remain some risks despite of the adaptations of the concentration of the nutrient solution. Consequently and regularly is meant, that an analysis for N, P, K, Mg, salt (EC), and pH must be done every 4 weeks. The estimated optimal values are given in table 1.

Losses of nitrogen by denitrification

Normally, in recirculating systems N-losses should not occur. But during the course of experiments with such systems Zerche and Kuchenbuch (1995) observed N-losses of about 30 %. Results of Daum & Schenk (1997) indicate, that N could escape as gas, e.g. N_2 or N_2O. Furthermore, it was observed that these losses increased if the N-concentration in the nutrient solution was high, the pH-value was above 6.0, the temperature of the substrate was higher than 20 °C, and when the root density rose (Daum & Schenk, 1997). On the other hand, Schenk et al. (1997) reported on gaseous losses of nitrogen, during the composting period of organic material. These findings clearly indicate, that such cultivation systems, either in thin layers of organic material or recirculating, have only a closed root zone, but they are not completely closed.

Water quality

Limiting values for the water quality to be used for recirculating systems can be seen from table 2. These values correspond to values for cultivation in horticultural soils under glass. The NO_3-N-contents of the irrigation water should be taken into consideration for the calculation of the desired N-concentration of the nutrient solution. Furthermore, the water should be about greenhouse temperature (18 °C).

The optimal temperature of root zones in soils and substrates is situated in between 18 and 25 °C, depending on plant species. This is valid for hydroculture as well. Due to evaporation of water from the root zone, the temperature is about 1 to 2 °C below the respective air temperature. Plants like tomatoes, chrysanthemums, and lettuce respond positively to temperature increases. On the other hand, high temperature in the root zone leads to a lack in O_2-content, reduction of root growth and therefore Ca-uptake (Schenk & Brumm, 2008).

Table 2. Water quality recommended for soilless cultivation (Brumm & Schenk, 2008).

Nutrient element	Requirements	
Ca	< 80 bls 100mg/l	All nutrient elements to be considered while fertilizing
Mg	<30 mg/l	
NO_3		
K		
Salt contents		<500 mg KCl/l
Na		< 30 - 50 mg/l
Cl		< 30 - 50 mg/l
B		< 0,5 mg/l
Fe		<1 mg/l
Zn		<1 mg/l
Carbonate Contents		5 -10 °dKH (= 1,78 - 3,56mmol/l Säurekapazität) = Acid capacity

If plants are cultivated in thin layers of substrate (< 5 cm), the salt-content of the water (EC-value) should be considered, because during the course of time salt contents of the substrate can increase. Due to this fact, not only for recirculating systems but also for cultivation of plants in thin layers, rain water should be captured and used for irrigation.

Water quantity

As can be seen in table 3, the average water consumption of plants is mainly related to the cultivation method. Consequently, by the application of modern methods of recirculation the amount of irrigation water can be tremendously reduced, e.g. 66 % in the case of pot plant production and up to 25 % for cut flowers or vegetables. It should be mentioned that these reductions are valid for protected cultivation under glass or shelter.

Table 3. Average water use in different cases of ornamental plant production (Roeber, 2008)

Method of water application	water use in m³/m² x year
Pot plants	
Traditional, by hand	1.2 to 2.4
Drip irrigation	0.8 to 1.6
Recirculation: ebb and flow, gullies	0.4 to 0.8
Cultivation in beds (cut flowers, vegetables)	
Traditional, by hand	0.8 to 1.5
Soilless cultivation (horticultural substrates)	0.8 to 1.5
Recirculating soilless cultivation	0.6 to 1.1

Plant protection

Because of the experiences with the cultivation of plants in thin layers of substrate it can be assumed that the measures for plant protection are to be reduced due to the reduction of soil-borne pests and diseases (Leinfelder et al., 1990). For the cultivation in thin layers of substrate, there is no necessity for costly filter systems as well as for systems with drain water reuse. When used for the first time the substrate must not be steamed. Depending on plant species cultivated, it must be decided, whether the substrate should be reused after steaming or be composted and renewed. Experimental results showed that a replanting of *Chrysanthemum* x *grandiflorum* after *C.* x *grandiflorum* was possible even without any steaming of the substrate (Leinfelder & Roeber, 1990).

Hydroponic recirculating systems

As compared to the cultivation in thin layers, in recirculating systems the nutrient solution is applied as an overdrain of about 30 to 50 %, the excess solution collected and rensed in the next irrigation cycle. But the nutrient solution is to be processed before reuse. These systems can either work by subirrigation or ebb-flow or hydroponically. A description of the different systems is given below and can be seen from figure 5 (Meyer, 1996).

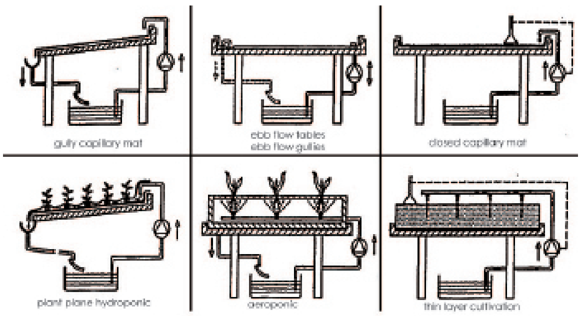
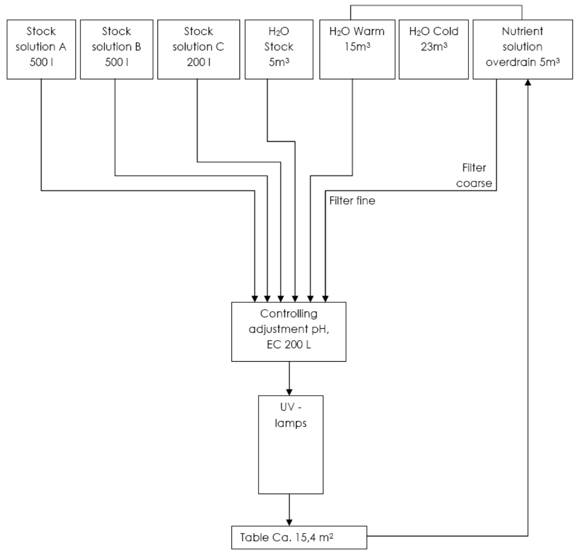


Figure 5. Schemes of recirculating irrigation systems (after Meyer, 1996)

The ground, on which the system is located, has to be prepared nearly the same way as for cultivation in thin layers, except that a 1% slope is required allowing the drainage of the nutrient solution into a catchment tank. Figure 6 shows the set-up of this system in principle (Klinkan et al., 1991).



Stock solution A: 100g L^{-1} 2/11/39/4 + micronutrients)
Stock solution B: 100g L^{-1} $Ca(NO_3)_2$ (15,5% N)
or
74g L^{-1} $(NH_4)_2SO_4$ (21% N)
Stock solution C: 100g L^{-1} 15/7/22/6 + micronutrients

Klinkan et al. 1991

Figure 6. Set-up of a recirculating system (Klinkan et al., 1991) for ebb-flow or hydroponics

There are different hydroponic recirculating systems available. They can be driven either with or without substrate.

Aeroponic system

In aeroponics, the bare root system is continuously in contact with the circulating nutrient solution (Molitor, 1990). It is sprayed with the solution (see figure 7) from time to time depending mainly on solar radiation. All parts of this system must work without any interruption, because otherwise the roots will dry out very quickly. Furthermore, all material used should be either plastic or stainless steel material due to corrosion problems and/or solving of metals contaminating the plants. The advantages of the system seem to be the simple regulation and nearly no problems with waste disposal. Disadvantages, on the other hand, are relatively high energy requirement and the necessity of absolute reliability of all components and their functioning without any interruption. 30 min of interruption of the function of such systems can be good enough for a complete destruction of the plants, because there is no water buffer.

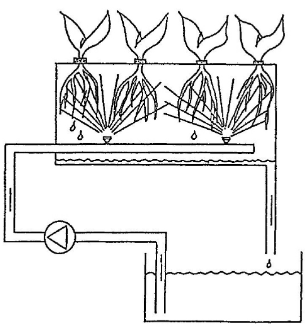


Figure 7. Aeroponic system (Alt et al., 1989)

Plant plane hydroponic system

In this case, the roots of the plants are growing between two layers of plastic film. The space is filled with a textile material or just organic material. The plastic film underneath separates the system from the soil and the upper film, mostly white coloured, reduces unproductive evaporation and the growth of algae. The white colour increases the light reflection. The capillary properties of the layer between the two plastic films results in an uniform distribution of the nutrient solution (Kadner, 1995). This system can be regulated by a switch tensiometer with a flat base. The installation of the tensiometer reduces the amount of drainwater.

Nutrient film technique

This system is the oldest of the hydroponic systems in horticultural practice, which sometimes is still in use. The roots of the plants are floating directly in the nutrient solution (Cooper, 1979). Plants are difficult to grow in it, due to problems with their fixation, e.g. tomatoes or cut flowers.

Hydroponic systems with substrate

Increasing protected areas of plant production can be found where hydroponic systems with substrates like rockwool, expanded clay material, foam of polyurethane, perlite, pumice, and others or mixtures of them are in use. Substrate layers from 5 to 20 cm or the substrates filled into containers with holes 3 cm above the bottom are utilized. In both cases the nutrient solution can drain and be recirculated in special pipes or plastic channels (figure 8; Roeber, 1996).

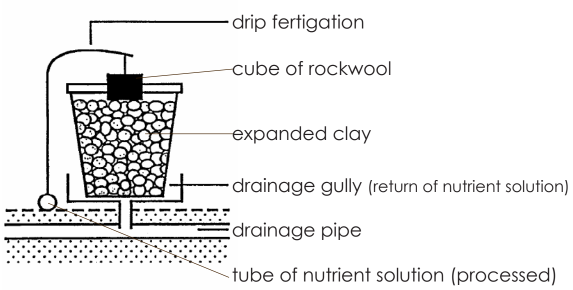


Figure 8. Container filled with expanded clay

Pipes or channels should have a slope of about 1 % for a better runoff of the nutrient solution. The nutrient solution must be applied with 30 to 50 % overdrain for a better recirculation and leaching of salts. The processing of the recirculating nutrient solution consists of an amendment of pure water or addition of a stock solution (figure 6). This mixing process is controlled by a special computer system (Klinkan et al., 1991). On the other hand, the nutrient solution must be filtered to eliminate pests and diseases. Furthermore, the nutrient solution has to be analyzed every four weeks to control changes in the composition due to mistakes of the dosage (Mewes et al., 1994).

On the other hand, it can be useful to analyze the leaves of the respective plants and to compare the results with given standards (Meinken, 2008). These analyses may be carried out every six months or in the case of nutritional disorders. Schacht & Schenk (1997) reported about the validation of a simulation model to control fertilization of greenhouse cucumbers in soilless culture by means of a NO_3-N sap test. The NO_3-N sap test was proven to be a suitable tool for checking simulated nutrient supply and to adjust the simulation model. Possibly, this model can be used for other plants in future.

Furthermore, Mewes et al. (1994) found, that the hydroponic system with expanded clay as a substrate can be used with the same technique of fertilization (application of a certain concentration) as already mentioned. The technique of pH-regulation, described by Jungk (1970) and developed by Molitor (1985) for horticultural practice, can be used for the cultivation of plants with great success and has a lot of advantages as compared to the system of the application of a nutrient solution derived from stock solutions prepared with single salts.

The correction of the pH-value depends on the values of the analysis of the drained nutrient solution. The adjustment of the pH-value is possible by the use of a two-component fertilizer, as proposed by Molitor (1985), using:

A. N as $(NH_4)_2SO_4$ for a reduction of the pH-value or N as NH_4NO_3 for keeping the pH-value at about the level proposed or N as $Ca(NO_3)_2$ for an increase of the pH-value;
B. a basis fertilizer containing all the other macro- and micronutrients, except N.

All the hydroponic systems use the concentration of the nutrient solution and the contents of single elements for regulation of growth and quality. The effects of different fertilizers for the supply of the plants with nutrients have been described in detail by Brumm & Schenk (2008).

Due to the fact that the nutrient solution is always applied to the substrate from above, a disinfection of the solution is necessary. There exist several possibilities for disinfection, which have been described and compared (Runia, 1995; Wohanka, 1990, 1995, 2004). The simplest way of disinfection seems to be the method of slow filtration of the nutrient solution through a filter bed. The great advantages of this method are the low cost and the high degree of safety. But on the other hand, there is a need of 1 m^2 filter area for the decontamination from 3.0 to 7.0 m^3 of solution per day (Wohanka, 1990). Further possibilities for keeping the nutrient solution clean are the application of Cl_2, UV-radiation, heat (100 °C), O_3, and ultrafiltration (microfilter) or newly ClO_2, but they are far more expensive than sand filtration (Wohanka, 2004) and in some cases they are harmful to the plants.

Conclusion

European authorities are looking for possibilities of a reduced use of agrochemicals. Among these, fertilizers play an important role, because their nitrogen can be leached out and get into the underground water. Perhaps, changing the fertilizing technique and avoidance of wasting fertilizer and water can help reaching the goal of environment-friendly cultivation. Even when cultivating in the open air, e.g. trees, shrubs, perennial plants, such methods are in use with great success (Alt, 1998; MacCarthaigh, 2008).

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