Disease Management in Soilless Culture Systems

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Abstract

EU legislation, laid down in the Water Framework Directive, demands to minimize emissions of nitrogen, phosphate and crop protection products to achieve an excellent chemical and ecological quality in 2015. The aim is to force growers to a better water and disease management. Supply water of excellent chemical quality will have to be recirculated as long as possible, for which adequate disinfection equipment have to be used. Several sources of water are used as supply water. Rainwater is chemically best, followed by reverse osmosis water. However, the latter is rather expensive. Tap water and surface water often have a too high salinity, while well water may vary dramatically from place to place. Rainwater and surface water are potential risk factors for importing soil-borne pathogens. Disinfection of the recirculating nutrient solution can be done adequately by heat treatment and UV radiation. Membrane filtration performs well, but is mostly too costly. Chemical treatments as sodium hypochlorite, chlorine dioxide and copper silver ionization may partly solve the pathogen problem, but introduce a potential accumulation of other elements in closed systems. Hydrogen peroxide, chlorine dioxide and sodium hypochlorite perform better to clean pipe work instead of soil-borne pathogens.

INTRODUCTION

Soilless cultures or hydroponics were introduced to avoid soil-borne diseases, but also to avoid the use of the soil disinfectant methyl bromide. Soilless culture increased production and quality of the produce by improvements in control compared to a traditional soil grown crop. In return other pathogens appeared in the nutrient solution which could disperse very rapidly. Closed systems were promoted to decrease emission of nutrients to the environment and to improve the water efficiency (Van Os, 1999).

From the beginning of soilless cultures it was said that chemical elimination of pathogens which are spread in the recirculating water would be a dead end. There were not enough chemicals, development of new pesticides for a relative small market would not be cost effective, and resistance of pathogens against the pesticide will appear soon. Besides, legislation of individual countries and of the European Union (EU) became stricter. Since 2000 the EU Water Framework Directive (EU WFD, 2000) is in force, having the ultimate goal to have an excellent chemical and ecological quality of ground and surface water in the member states in 2015. Practically it means that no emission of nutrients and chemicals is allowed.

In this paper a relation will be laid between disease management and water management to minimise the risk for dispersal of pathogens all over the nursery and to decrease the emission of nutrients and crop protection products (chemicals) to the environment.

WATER FLUXES AS SOURCE OF DISEASE DISPERSAL

An analysis has been made of the water fluxes entering and leaving the greenhouse (Fig. 1) with a focus on the risk for pathogen dispersal. Incoming water flows are:

- Rainwater: best chemical quality water, but it may contain pathogens because most of the rainwater collection tanks stand outside and are not covered. As rainwater is collected from the cover of the greenhouse spores of pathogens may be washed off too. Hardly any information is available about the diversity and the intensity of spores or, in other words, the potential risk;

- Tap water: no risk for plant pathogens, but in general too much sodium for continuous recirculation and too expensive;
- Surface water: high risk for pathogens. Besides there is a high risk for intake of salts and pesticides;
- Well water: no risk for plant pathogens. Chemical quality may vary depending the place of the well;
- Condensation water: hardly any risk for plant pathogens because root-borne pathogens have to survive in dry conditions. In the Netherlands this water type has to be collected and to be reused as supply water;
- Reverse osmosis water (RO): in the Netherlands RO will be applied on well water or, sometimes, on surface water. In both cases the filtrate (about 50% of the outcoming water flux) will not contain any spores of plant pathogens. The brine (the other 50%) contains the salts and pathogens, in case of use of surface water, and is generally pumped back to the well water layer from where it was pumped up. Chemically RO water is of excellent quality but expensive.

In the strategies for disinfection of the recirculating water it is sometimes recommended to disinfect the incoming (rain)water too, additional to the drain water. However, there is no information about doing this, but in a densely greenhouse area it should be recommended to minimise the risks to import pathogens.

Referring to EU WFD (2000) 100% recirculation of the nutrient solution will be needed. In that case supply water needs an excellent chemical quality. Then rainwater is preferred. Additionally RO water should be recommended. Other water sources may contain much more sodium resulting in the need to leach nutrient solution to surface water or the sewage system. Tap water, surface water and occasionally used “grey” water (waste water from households or industry) contain too much sodium for continuous recirculation.

Even in the Netherlands rainwater is mostly not sufficient to cover the complete water needs of a nursery. A rainwater storage of 3000 m^3/ha may be sufficient in many years (average precipitation 800 mm/yr in combination with a uniform distribution over the 12 months), but it is insufficient in dry years (precipitation less than 600 mm/yr). In Mediterranean countries water coverage by rainwater is mostly insufficient (less precipitation, higher transpiration and a more concentrated fall in only 5-7 months). Here, rainwater collection is still recommended because of the low price and good chemical quality. Other water sources are always needed and an economical consideration is needed to decide which source is most efficient.

Increased application of technology shows a dramatic increase in the water use efficiency of a crop (Stanghellini et al., 2003). In case of open field production of tomato about 15 kg of fresh tomato can be produced per m^3 water, while in a Dutch climate controlled greenhouse with CO_2 enrichment 45 kg tomatoes can be produced per m^3 and in a closed hydroponic growing system even 65 kg per m^3 water. A similar increase in efficiency of the use of fertilizer can be achieved in a closed hydroponic growing system. At the same time the amount used must be of excellent chemical quality and may not contain spores of plant pathogens to minimize the risk of loss of production.

Outgoing water fluxes (Fig. 1) are discharge water (imbalanced nutrient solution by high sodium level) and filter cleaning water (for automatic cleaning of filters). They may contain plant pathogens as they are not disinfected. If discharge takes place to surface water it may be an input flow for neighboring companies. The leakage out of the system leaves the nursery via the soil as a diffuse source; it contains pathogens, but will not be harmful for others.

WATER DISINFECTION METHODS

The surplus of water given to the plants (drainwater) has to be reused. A surplus has to be given to equalize differences in temperature in the greenhouse, release of the drippers and individual plant growth. In many countries an open system is still in use, but following the EU WFD (2000), it will not be permitted anymore because of the emission of nutrients and chemicals to the environment. Reuse and, consequently, purification has to take place. The leading principle should be to recirculate as long as possible and finally, in case of emergency, to leach a part of the solution to a sewage system or surface and ground water. For recirculation it is strongly recommended to disinfect the nutrient solution to minimise risks of dispersal of spores. In the Netherlands all soilless growers use disinfection equipment in the so-called closed systems, but many still have an outgoing water flow of 10-40%. It appeared that not only sodium is a (legal) reason to leach solution, but also other factors like fear for diseases in early stages of growth, growth inhibition by substances, too small designed water tanks and technical failure of equipment are important reasons to discharge the nutrient solution. Although costs of fertilizer rose last years, the costs for water, fertilizer and chemicals are far below 10% of all annual costs.

For a greenhouse of 10000 m^2, a disinfection capacity of about 10-30 m^3/day is needed to disinfect an estimated needed surplus of 30% of the water supplied with drip irrigation to tomato plants during a 24 h period in summer conditions. Because of the variable return rate of drain water, a sufficiently large catchment tank for drain water is needed in which the water is stored before it is pumped to the disinfection unit (Fig. 1). After disinfection another tank is required to store the clean water before adjusting EC and pH and blending with new water to supply to the plants. A great number of methods to disinfect the nutrient solution are available, below an overview.

Physical Methods

In general physical methods don't alter the chemical composition of the solution and there is no build up of residuals.

1. Heat Treatment. Heating the drain water to lethal temperatures is the most reliable method for disinfection. Each type of organism has its own lethal temperature. Non-spore forming bacteria have lethal temperatures between 40 and 60°C, fungi between 40 and 70°C, with some exceptions to 85°C, nematodes between 45 and 55°C and viruses between 80 and 95°C (Runia et al., 1988). Generally the temperature setpoint (95°C) is high enough to kill most of the organisms that are likely to cause diseases during the period of time that the liquid is at these killing temperatures (minimal exposure time 10 s). Although this may seem very energy intensive, it should be noted that the energy is recovered and reused with heat exchangers. However, availability of a cheap energy source is of importance for economic reason.

2. UV Radiation. UV radiation is electromagnetic radiation with a wavelength between 200 and 400 nm. Wavelengths between 200 and 280 nm (UV-C), with an optimum at 254 nm has a strong killing effect on micro-organisms, because it minimizes the multiplication of DNA chains. From experiments it is known that different levels of radiation are needed for different organisms so as to achieve the same level of efficacy. Runia (1995) recommends a dose which varies from 100 mJ/cm^2 for eliminating bacteria and fungi to 250 mJ/cm^2 for eliminating viruses. These relatively high doses are needed to compensate for variations in water turbidity and variations in penetration of the energy into the solution due to low turbulence around the UV lamp or variations in output from the UV lamp.

3. Membrane Filtration. Filtration can be used to remove any material out of the nutrient solution. Various types of filters are available relative to the range of particle sizes. Rapid sand filters are often used to remove large particles from the drain water before adding, measuring and control of EC, pH and application of new fertilizers. After passing the fertiliser unit often a fine synthetic filter (50-80 µm) is built in the water flow to remove unsolved fertilizer salts or precipitates to avoid clogging of the drippers. These synthetic filters are also used as pre-treatment for disinfection methods as heat treatment, ozone treatment or UV radiation. With declining pore size, the flow is inhibited, so that removal of very small particles requires a combination of adequate filters and high pressure followed by frequent cleaning of the filter(s). Removal of pathogens requires relatively small pore size (<10 µm; so-called micro-, ultra- or nanofiltration).Various membrane filtration technologies are available where water under high pressure is pressed through a membrane. The water is divided in the required clean water (filtrate) and the remaining water with concentrated salts (the so-called brine) and pathogens. The investment in a reliable filter system is still high, therefore it is only additionally used as method for the removal of pathogens. All over the world there is far more use of reverse osmosis (removal of ions, <0.001 µm) to desalinate seawater or other "grey" (waste) water to be used as supply water for the plants.

4. Slow Sand Filtration. Slow sand filtration (SSF) is considered to be a reliable, low-cost solution to eliminate soil-borne pathogens (Wohanka, 1995; Van Os et al., 1997b; Runia et al., 1997; Ehret et al., 2001) in greenhouse horticulture. *Phytophthora* spp. and *Pythium* spp. can be eliminated completely by this method, but *Fusarium* spp., viruses and nematodes are only partly (90-99.9%) removed by this method. The principle is based upon a supernatant water layer, which trickles slowly through a sand layer. Experiments proved that a flow rate of 100 L/m^2/h increases the performance compared to higher flow rates and so does the selection of finer sand (grain size 0.15-0.35 mm; D_{10}<0.4 mm) compared to coarser sand (Van Os et al., 1997a, b). Satisfactory performances can also be obtained when either the grain size increases to 1 or 2 mm or the filtration rate increases to 300 L/m^2/h (Wohanka et al., 1999). The mechanism of elimination is not only filtering (mechanical) as the size of the pores is generally larger than the pathogens eliminated. The forming of a biological active filter skin upon top of the sand appeared to be of great importance (Wohanka et al., 1999).

Chemical Methods

1. Ozone (O_3). Ozone is produced from dry air and electricity using an ozone-generator (converting $3O_2 \rightarrow 2O_3$). The ozone-enriched air is injected into the water that is being sanitized and stored for a period of 1 h. Runia (1995) concluded that an ozone supply of 10 g/h/m^3 drain water with an exposure time of 1 h is sufficient to eliminate all pathogens, including viruses. Human exposure to the ozone that vents from the system or the storage tanks should be avoided since even a short exposure time of a concentration of 0.1 mg/L of ozone may cause irritation of mucous membranes. Therefore, ozone treatment is not very popular (expensive, strict rules), although it works technically well. A disadvantage is the inability to process large quantities of water at the same time. Another drawback of the use of ozone is that it reacts with iron chelate. Consequently, higher dosages of iron are needed and measures need to be taken to deal with iron deposits in the system.

2. Hydrogen Peroxide (H_2O_2). Hydrogen peroxide is a strong, unstable oxidizing agent that reacts to form H_2O and an $O^{\cdot}$ radical. Commercially so-called activators are added to the solution to stabilize the original solution and to increase the efficacy. Activators are mostly formic acid or acetic acid, which decrease pH in the nutrient solution. Different dosages are recommended (Runia, 1995) against *Pythium* spp. (0.005%), other fungi (0.01%) as Fusarium and against viruses (0.05%). The 0.05% concentration is also harmful for plant roots. Hydrogen peroxide is especially helpful for cleaning the watering system, while the use for disinfection has been taken over by other methods. The method is inexpensive, but not efficiently.

3. Sodium Hypochlorite (NaOCl). Sodium hypochlorite is a compound having different commercial names (household bleach) with different concentrations but with the same chemical structure (NaOCl). It is widely used for water treatment, especially in swimming pools. The product is relatively inexpensive due to this widespread use. When added to water, sodium hypochlorite decomposes to HOCl and $NaOH^-$ and depending on the pH to OCl^-, the latter decomposes to Cl^- and $O^{\cdot}$ for strong oxidation. It reacts directly with any organic substance and if there is enough hypochlorite it also reacts with pathogens. Le

Quillec et al. (2003) showed that the tenability of hypochlorite depends on the climatic conditions and the related decomposing reactions. High temperatures and contact with air causes rapid decomposition, at which $NaClO_3$ is formed with phytotoxic properties. Runia (1995) showed that hypochlorite is not effective for eliminating viruses. Chlorination with a concentration of 1-5 mg Cl/L and an exposure time of 2 h achieved a reduction of 90-99.9% of *Fusarium oxysporum*, but some spores survived at all concentrations. Safety measures have to be taken for safe storage and handling. Hypochlorite might work against a number of pathogens, not all, but at the same time Na^+ and Cl^- concentration is increased in a closed growing system which will also lead to levels which decrease productivity of the crop and at which the nutrient solution has to be leached. Despite the above-mentioned the product is used and recommended by others as a cheap and useful method.

4. Chlorine Dioxide (ClO_2). A yellowish gas can be formed on-site by combining hydrochloric acid and sodium chlorite, but this will be explosive and instable. It has to be solved into water to stabilize it and where it is highly soluble. Even solved in water chlorine dioxide easily decomposes in sunlight. The efficacy is optimal in a wide pH range between 4 and 10 (Lenntech, 2008). It is even very active at a high organic load of the water. Strict safety measures have to be taken for the workers. The forming of trihalomethanes (carcinogenous) is much less compared to other chlorine products because the working is mainly based on oxidation in stead of substitution. It is mostly used as a disinfectant where it is able to eliminate biofilms completely. Little is known about disinfection of recirculating solutions. Mebalds et al. (1996) reports about its efficacy against a number of soil-borne pathogens (*Phytophthora cinnamomi*, *Pythium ultimum*, *Fusarium oxysporum*) in dosages varying between 1 and 5 ppm at an exposure time of 10 min. Much more information is available on its efficacy against *Legionella*, *E. coli* and *Bacillus* spp. (Zhang, 2007), whereas it is in use to disinfect drinking water and waste water or for cleaning equipment (Ritenour, 2001).

5. Copper Silver Ionization. Electrolysis of water by silver and copper electrodes releases positive charged free Cu^+ ions in the water, which react with membranes of micro-organisms. Runia (1995) did not find a log 3 (99.9%) reduction for tomato mosaic virus and for *Fusarium oxysporum* after a treatment of 2 h, 1 or 4 days. Recently released commercial equipment (Anonymous, 2005) claims disinfection of the nutrient solution with an adjustable input of Cu ions. It is a disadvantage that the Cu input in the nutrient solution is much higher than the plant needs, which will lead to toxic levels in closed systems. However, pot plant growers claim a better growth and less loss of plants when using the apparatus. Another negative aspect is the release of heavy metals (silver, copper) into the environment, which is restricted by law in many countries.

6. Active Carbon Adsorption. Active carbon is specially produced to achieve a big internal surface area (500-1500 m^2/g) for adsorption of mainly organic, non-polar substances. Also halogenated substances, odours and tastes can be adsorbed (Lenntech, 2008). Water flows constantly through the carbon realizing an accumulation of substances in the filter. Regeneration of the filter has to take place when it looses 5-10% of its efficacy. The method is used for drinking water treatment but not very much used for the removal of pathogens. The method is too expensive, while performance is insufficient. An additional disadvantage is that a big part of the fertilizing elements may be removed from the solution, which makes fertilization much more expensive.

OTHER ASPECTS OF DISEASE MANAGEMENT

Substrate disinfection is a decreasing action and replaced by single year use. Between two crop growers have little time to execute the heavy and uncomfortable work of collecting slab, steam sterilizing them in a container and replacing them in the greenhouse. Preliminary investigations have been taken to design a mobile steaming apparatus for on-site slab disinfection. Here, the transport of the steam and the time needed to disinfect the slab are limiting factors for technical and economic application. Drippers are collected at the crop change and plunged in a chemical solution, while plastic sheets are removed and replaced by new ones. System design in most fruit vegetables was adapted to avoid drainwater from one plant to pass along the roots of another plant. Then, in-row infection can be avoided. Hygiene practices are common to minimize the risk that pests and diseases enter the nursery via visiting people.

DISCUSSION

No Open Soilless Systems

The EU WFD (2000) is clear in saying that the surface water quality should be excellent again by 2015 and that member states should make plans about how to improve the quality. Those plans are submitted to EU in 2008 and EU will judge them in 2009. Dutch greenhouse horticulture (Werkgroep Emissienormen, 2008) already said to strive to an almost zero emission in 2027. They take an advance on two periods of 6 years which are presented in the WFD for phasing to achieve the demanded goal later, in 2021 or 2027.

It became also clear that closed soilless growing systems in the Netherlands are not completely (100%) closed, between 10 and 40% of the supplied water finally reaches the sewage system or surface water. Reasons for leaching or loosing such amounts are not always clear. Sodium in the supply water is the main, legal, reason for leaching, but growth inhibition, leakages of the system or wrongly dimensioned water tanks may be other reasons. Investigations by the growers association LTO are already started to measure and to register emissions to achieve reliable data.

For soil grown greenhouse crops other solutions have to be found. Once again there is great interest to change the soil-grown growing method into a soilless method for crops such as chrysanthemums, freesia, alstroemeria and leaf vegetables. The main problem is not technically, but an economic one; investment is too high, production or quality increase is too low. Now, outside cropping methods are also subject for investigation if a change to a soilless system is possible (De Haan and van Wijk, 2007). Pilot crops will be lettuce, strawberry and leek. Here, investment level is much lower compared to greenhouse production, while systems have to be very robust because of weather conditions. However, preliminary results with lettuce and leek (Van Os et al., 2009) look promising. This is reason to extend the investigations to crops in other sectors such as berries (red currant, blackberry), nursery stock and bulbs. Here disease management will appear again, slightly different because of outside conditions, but with the same main headline that in wrongly designed systems diseases as pythium and phytophthora take there chance.

Disinfection

Drainwater of closed soilless systems should be preferably disinfected before reuse. In the Netherlands the main methods are still heat treatment and UV radiation. Heat treatment is becoming less popular because of the demanded energy input, but also because UV radiation performs well, at which both low and high pressure lamps are used and the actual radiation is constantly measured. If, by age of the lamps, radiation decreases the flow rate of the water is automatically adapted and the grower will be alarmed if performance becomes below a minimum level. A similar adaptation takes place if the turbidity of the solution increases too much. Slow sand filtration was developing in the Mediterranean countries because of the low investment and reasonable good performance.

A number of methods based on chlorine activity (sodium hypochlorite, chlorine dioxide) or releasing heavy metals (copper silver ionization) are bad examples for disinfection. On one side you eliminate (part of) the pathogens, and on the other hand you introduce elements which will accumulate to toxic levels for the plant in a (completely) closed system. They are not a sustainable solution. The oxidizing agents (ozone and hydrogen peroxide) sometimes also have the disadvantage of introducing toxic levels to the roots. However, the main disadvantage is the uncontrollable reaction on organic matter which varies dramatically in the solution. You are not always sure that because of the variation in composition the pathogens are all eliminated.

Membrane filtration is able to eliminate both pathogens and nutrients and even chemicals, but pre-treatment in combination with investment and maintenance make the system still expensive for use in a greenhouse. It will be better to use this method to purify the incoming supply water, for one grower or a group of growers in a certain area.

Practically growers do prefer a method with an excellent performance in combination with low costs. A good performance can be described by eliminating pathogens with a reduction of 99.9% (or a log 3 reduction) and a clear, understandable and controllable process. Heat treatment, UV radiation, ozone treatment and membrane filtration show a good performance. However investments in ozone treatment and membrane filtration are very high, resulting in high annual costs. Heat treatment and UV radiation show also high annual costs, but investments are lower, while the eliminating process is easy controllable. The latter two methods are most popular among growers, especially at nurseries larger than 1 or 2 ha. Slow sand filtration shows a slightly lesser performance but considerably lower annual costs. This method could be recommended for nurseries smaller than 1 ha. Sodium hypochlorite and hydrogen peroxide are also cheap methods, but performance is insufficiently. Chlorine dioxide, copper/silver ionization and active carbon adsorption combine a poor performance with high costs. Probably the performance of chorine dioxide can be improved after appropriate investigations (dosage-effect relation), but safety measures may still lead to high costs.

Bio Fouling and Pretreatment

Disinfection methods are not very selective between pathogens and other organic material in the solution. Therefore pretreatment (rapid sand filter, 50-80 um mechanical filter) of the solution before disinfection is recommended at heat treatment and UV radiation. Sometimes pH adaptation is needed too (heat treatment, several oxidizing methods). If after disinfection residuals of chemical methods keep in the water they may react with bio films which have been formed in the pipe lines of the watering systems. If the bio film is released from the walls they will be transported to the drippers and cause clogging there. Several oxidizing methods (sodium hypochlorite, hydrogen peroxide with activators, chlorine dioxide) are mainly in use to clean pipe lines and equipment. They give a special risk for clogging of drippers if used in equipment already in use for a certain time.

CONCLUSIONS

Incoming water fluxes, such as rainwater, are a potential risk for dispersal of plant pathogens. In commercial practice this risk is mostly neglected. In overall disease management this factor should be taken into account. Discharged water fluxes to surface water are mostly contaminated with plant pathogens and, consequently, are a risk for neighboring greenhouse companies which want to use surface water.

The EU Water Framework Directive forces growers to minimize emissions of nutrients and chemicals to ground- and surface water. It implicates that closed systems have to be closed for 100% and should not have a discharge of 10-40%. It also implicates that open systems has to be closed and that emissions of nutrients and chemicals can only be minimized if a chemically excellent water quality is used. Technology level of greenhouse companies will further increase. Disease management will become more important again because more growers will apply a closed soilless growing system. There will be no longer an excuse for discharge to compensate poor management.

Various physical and chemical methods are available for disinfecting the recirculating nutrient solution. Growers prefer a good performance with low annual costs. Heat treatment and UV radiation are best methods for disinfection. They combine a good performance with reasonable costs. Slow sand filtration is a good method if the investment level should be low. Membrane filtration and ozone treatment show a good performance in eliminating pathogens, but the methods are generally too expensive.

Sodium hypochlorite, chlorine dioxide and hydrogen peroxide with activators are methods to clean pipe lines and equipment, but they are less suitable to eliminate pathogens completely. Copper silver ionisation cannot be recommended now for use as disinfection method, disadvantages are too big. Active carbon adsorption is not a disinfecting method, it can be used to eliminate certain substances to purify the solution.

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Figures

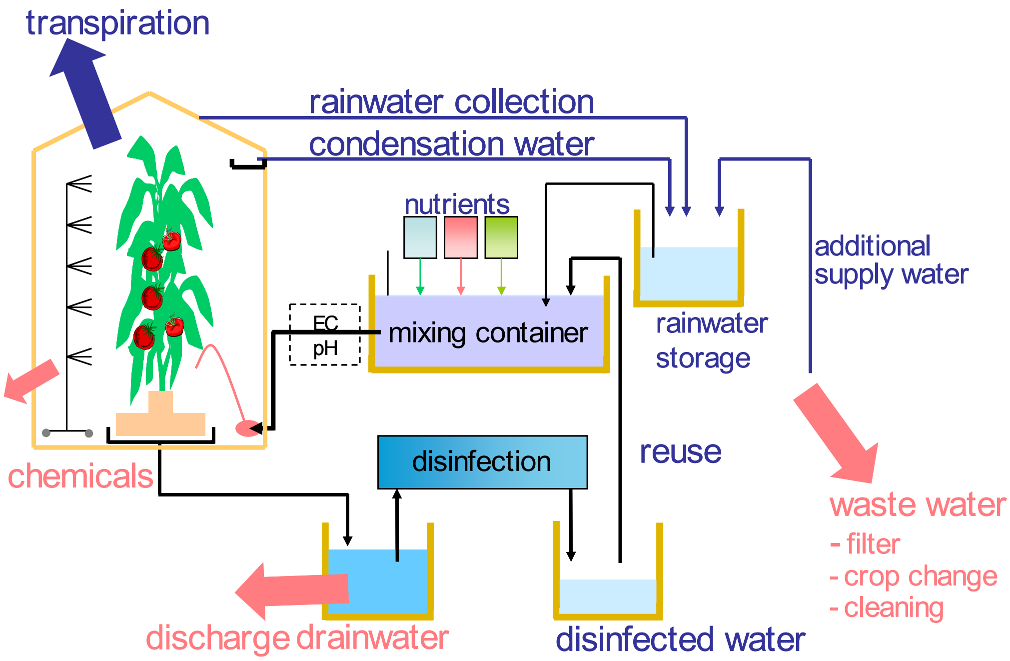

Fig. 1. Flow chart of water fluxes in a greenhouse with soilless culture.