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Hans-Peter Kläring

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Review article

Strategies to control water and nutrient supplies to greenhouse crops. A review

Hans-Peter KLÄRING*

Institute of Vegetable and Ornamental Crops Großbeeren/Erfurt e.V., Theodor-Echtermeyer-Weg 1, 14979 Großbeeren, Germany

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Abstract – This paper introduces the approaches to automatic control of water and nutrient supplies to greenhouse crops. The traditional concepts of surplus irrigation and fertilization conflict with the environmental aspect. Therefore, water and nutrient demands of the plants must be met by the supplies. The generally used strategy is based on the application of standard nutrient solutions and frequent analyses of the nutrient solution concentration in the root environment. An improvement to this strategy is expected by using a feedback control, which takes ion sensitive measurements of the drainage water concentration or a feedforward control, where nutrient and water uptake are predicted using growth and transpiration models. Most of these approaches are still on a theoretical level and are far from being practical applications. Current strategies are directed towards the synchronization of uptake and supply, but future strategies should control plant functioning.

control / greenhouse / nutrient solution / nutrient supply / water supply

Résumé – Mise au point : stratégies pour contrôler les apports d'eau et d'éléments nutritifs aux cultures sous serre. Cet article introduit les approches pour un contrôle automatique des alimentations en eau et en éléments nutritifs pour les cultures sous serre. Le concept traditionnel d'irrigation et de fertilisation excédentaires entre en conflit avec les aspects environnementaux. Cependant, les demandes d'eau et d'éléments nutritifs des plantes doivent être satisfaits par les apports. La stratégie utilisée généralement est basée sur l'emploi de solutions nutritives standard et de fréquentes analyses de la concentration de la solution nutritive dans l'environnement des racines. Une amélioration de cette stratégie est espérée en utilisant un système de rétroaction, qui prend en compte des mesures sensibles de la concentration ionique de l'eau de drainage, ou un système de réaction anticipée dans lequel les besoins en eau en éléments nutritifs sont prévus à parti de modèles de croissance et de transpiration. Ces approches sont pour la plupart d'entre elles, développées sur un plant théorique et sont encore loin des applications pratiques. Les stratégies actuelles sont dirigées vers la synchronisation des prélèvements et des apports, mais les stratégies futures devront contrôler le fonctionnement des plantes.

contrôle / serre / solution nutritive / apport de substances nutritives / apport d'eau

1. INTRODUCTION

The development of models and strategies to control the environment of greenhouse crops started with the shoot environment, that is, with the greenhouse climate. One important reason was that influencing variables such as temperature, humidity, irradiation or CO_2 concentration are easier to measure and to control. Moreover, expenses for artificial lighting, heating, dehumidification or CO_2 enrichment of the greenhouse air are

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* Correspondence and reprints
Klaring@IGZeV.de

many times higher than for irrigation and fertilization. The control strategies for the greenhouse climate, and the models behind them, assumed that water and nutrient uptake did not limit plant growth. This assumption was correct due to the surplus irrigation and fertilization at that time, both in soil and soilless growing systems. The related ground water contamination seemed to conflict with environmental considerations, and closed growing systems, in the sense of systems avoiding seepage of drainage water, were introduced. Moreover, conditions in the root environment became of interest in the control of product quality [19]. This was the starting point in the eighties for a strong intensification of research efforts into the effects of the root environment on plant growth and the yield of greenhouse crops.

The basis of all approaches for the control of nutrient and water supplies is the prediction of uptake by plants. Generally, there are three ways of controlling the supplies:

(1) adding amounts of water and nutrients expected to be taken up by the plants (quantity concept);

(2) controlling the water content and nutrient concentration in the root environment (concentration concept); and

(3) controlling the water content and nutrient concentration of the plant tissues (speaking plant concept).

Often two of these principles are combined in control approaches. The third method is not considered here, but is evaluated in the present issue of Agronomie by Ehret et al. [20].

Plant demands for nutrients and water are independent of the growing system (soil, substrates, water cultures or aeroponics) when water and nutrient uptake is not limited by conditions in the root environment. Water uptake, as affected by the shoot environment, has been investigated for many greenhouse crops. Models of transpiration depending on greenhouse climate were developed, parameterized and validated [e.g. 4, 72]. Nutrient uptake of crops is traditionally measured by dry matter analysis and related to growth curves. In soilless systems, these measurements are often completed using measurements of depletion of nutrients in the root environment [81], which allow a better resolution of nutrient uptake over time. Excellent reviews on modeling water relations and on modeling plant nutrition of horticultural crops were recently published by Jones and Tardieu [43] and Le Bot et al. [51], respectively.

Accurate data on water and nutrient uptake makes it possible to add the required amounts of water and nutrients, but this alone does not provide the uptake required for maximum plant growth and yield. Uptake is reduced when water content and nutrient concentration in the root environment are not sufficient [54]. In many experiments, optimal ranges for water content and nutrient concentrations in the root environment were obtained [e.g. 1]. Results of these experiments were specific to the crop and growing system under consideration. For this reason, control strategies for water and nutrient supplies have to take into account the peculiarities of both the crop and growing system.

Sophisticated models on the dynamics of water and nutrients were developed, including the uptake of water and nutrients that depends on the internal and external conditions of the roots [32, 58]. Heinen [33], this issue, briefly describes such a model and gives an example of the impact of different control strategies on the electrical conductivity in the root zone.

Even if the required combination of the different nutritional elements and water to supply the plants is known, a further problem may occur; there are restrictions in mixing nutrient solutions. The ionic balance constraint is the major reason for the impossibility of adding a single element to the nutrient solution or the growing substrate without adding or depleting other ions [73].

Nevertheless, in the research community, several efforts have been made to develop strategies for automatic optimal control of water and nutrient supplies to the plants. The present paper provides a brief survey of reports of these developments in the scientific literature. The necessity, the advantages and the limitations of the practical application of such solutions are discussed in relation to today's standard methods of irrigation and fertilization of greenhouse crops.

2. CONTROL STRATEGIES FOR SOIL

2.1. Traditional irrigation and fertilization

In general, the approaches to fertilization of greenhouse crops are similar to those in field production [e.g. 22]. The nutrient content of the soil is measured at the start of crop growth and sometimes several times during cultivation. Water and nutrients are applied to meet the expected uptake by the crop, taking into account the minimum content in the soil necessary for unlimited nutrient uptake, which is a parameter specific to the crop. A high surplus of water is often supplied to keep the soil moisture high and to avoid soil salinization [82]. Hence, additional fertilization is necessary to compensate for nutrient losses caused by leaching.

Water and nutrients are available to the plants for many days due to the large soil volume and the high target values for the water and nutrient content of the greenhouse soil (Tab. I). These target values are several

Table I. Available water and nitrogen in different growing systems related to a daily average and maximum uptake of water (2.5 and 8 $l \cdot m^{-2}$) and nitrogen (25 and 50 $mmol \cdot m^{-2}$) in a tomato crop grown all year round (adapted from Sonneveld [65, 66]).

Characteristic	Growing system			
	Soil	Peat bags	Rockwool	NFT
Substrate volume, $l \cdot m^{-2}$	300	25	14	-
Water capacity of substrate, % of vol.	25	50	70	-
Water content in root zone, $l \cdot m^{-2}$	75	12	10	4
Water content related to daily average/max uptake, d	30/9.4	4.8/1.5	4/1.3	1.6/0.5
Solution nitrogen concentration, $mmol \cdot l^{-1}$	25	23	23	12.5
Nitrogen content in root zone, $mmol \cdot m^{-2}$	1875	276	230	50
Nitrogen content related to daily average/max uptake, d	75/37.5	11/5.5	11.5/4.6	2/1

times higher than for field crops. For example, Lorenz et al. [53] recommend a target soil nitrogen value for growing tomatoes in the open field of 570 $mmol \cdot m^{-2}$ at the beginning and 285 $mmol \cdot m^{-2}$ at the end of the season. The recommended target value for greenhouse tomatoes is 1875 $mmol \cdot m^{-2}$ (Tab. I). The low costs of water and fertilizer compared to the high value of crops on the market, and the increased transition to soilless growing systems, may explain why so little research is being undertaken to develop more sophisticated control strategies for plant nutrition of greenhouse crops grown in soil. Field crop models based on nutrient balances were developed that took into account such processes as nutrient supply, nutrient uptake by the crop, leaching, absorption, mineralization and denitrification [e.g. 29]. Only recently, in connection with the quality aspect, have those models appeared for greenhouse crops. De Tourdonnet combined a soil behavior model and a crop growth model for lettuce that includes the processes of water and nitrate absorption [16]. In a modeling study, it was shown that this approach can be used to analyze the effects of irrigation and nitrogen fertilization on product quality (nitrate content and uniformity of the heads), and ground water nitrate pollution in greenhouse lettuce production [17, 18].

On the other hand, enhanced accuracy in the short-term control of nutrient and water supplies is not essential due to the high nutrient and water capacity in the root zone (Tab. I). In addition, the restraints in control options, in particular the impossibility of adding small doses of water by sprinkler irrigation and nutrients by gritting solid fertilizers, prevented more sophisticated control approaches and led to such high target values in the recommendations. This is probably why most fertilization and irrigation strategies are based on soil analysis and on measurements of soil moisture (by tensiometers), respectively.

2.2. Micro irrigation and fertilization

The introduction of simultaneous micro irrigation and fertilization (drip or trickle irrigation) in both the field and greenhouses opened up new possibilities for fine-tuning the control of water and nutrient supplies [6]. Recommendations for water and nutrient content in the soil can be lowered, and so the leaching fraction of water and nutrients can be reduced. The reservoir for water and nutrients in the soil may decrease due to a reduced volume of well-watered and fertilized soil, depending on distances between drippers and on irrigation rates [32, 45]. Although water or nutrient solutions are often supplied based on solar radiation, the main variables that are controlled in the soil are soil moisture and the nutrient content measured by soil analysis.

Efforts were made to further decrease the leaching fraction by utilizing drip irrigation systems based on measurements of soil moisture by tensiometers that aimed at a wet root environment with a dry soil layer beneath it [44]. Another approach by Liebig and Lippert [52] proposed the estimation of water uptake by the Penman equation and nutrient uptake by plant growth models. Estimated amounts of water and nutrients were supplied independently and trend analyses of measured and calculated soil water and soil nutrient status were used to readjust the control procedure. Whether there were differences in nutrient and water use efficiency and yield compared with surplus irrigation and fertilization was not reported.

3. CONTROL STRATEGIES FOR SOILLESS SYSTEMS

3.1. Surplus supply of water and nutrients in free drainage systems

In soilless growing systems, the reservoir of water and nutrients in the root zone is very small (Tab. I). For example, the water and nitrogen capacity in a rockwool slab may compensate for uptake by the tomato for a few days, but using the nutrient film technique (NFT) it may only be for a few hours. By comparison, for tomatoes grown in greenhouse soil, this compensation lasts several weeks. It follows that it is necessary to synchronize plant demands for water and nutrients in the short term to avoid deficiency of water and nutrients, or salinization in the growth medium.

The main strategy in substrate systems is to supply nutrient solutions via drip irrigation with a surplus of 30–50% of the water uptake by the plants. The drip frequency is usually based on solar radiation as it has the strongest impact on transpiration and water uptake by the plants. Nutrient solutions are designed based on measurements of the uptake by the plants. In many experiments the uptake of nutrients and water was measured and the ratios of the nutrient to water uptake calculated for the individual nutritional elements [e.g. 81]. These ratios are the basis for the composition of nutrient solutions [83]. The ratios change with the growth stage of the crop [76]. In fruit bearing vegetables such as tomatoes or peppers, the calcium to potassium ratio is significantly affected by the dry matter distribution among the vegetative and generative compartments due to their different nutrient contents. Standard solutions specific to the crops have now been published and applied [e.g. 68, 71]. Nutrient solutions are obtained by mixing highly concentrated stock solutions with water and the overall concentration controlled automatically as electrical conductivity (EC). However, nutrient solutions are "tuned" [71, p. 332] rather than calculated by models. A large amount of experience must often be used to compensate for the lack of knowledge on quantitative relationships. For example, it is recommended that bivalent ions be in the root environment at a 3–4 times higher ratio to water than their uptake ratio (Tab. II). Moreover, over the last few years, an increasing concentration of nutrient solution has been recommended for tomato to improve product quality [19]. Such recommendations are undisputed in general in regards to their qualitative effects, but quantitative parameters are taken from the experience of the corresponding author or adviser.

The application of nutrient solution of a constant concentration is sufficient in most situations in free drainage systems. A nutrient deficit only occurs when the supply concentration is smaller than the nutrient to water uptake ratio multiplied by the water uptake fraction (one minus leaching fraction). For example, following the recommendations of Sonneveld and Straver [68] for tomato in rockwool, deficiencies may only be expected in phosphorus (Tab. II). The recommended nutrient concentration in the root environment is between the drain concentrations calculated with the mean and the maximum nutrient to water uptake ratios. With an increasing leaching fraction, both come closer to the recommended concentration in the substrate. It is surprising that the recommended potassium and phosphorus concentrations in the root environment are not between the supply and mean calculated drainage water concentrations. For these elements, it is not possible to explain this by dissociation, complexation or precipitation reactions in the nutrient solution [14].

3.2. Nutrient solution concentration in the root environment – the target value to control

A major problem in substrate systems is to define and measure the nutrient concentration in the root environment. Although it is one of the most important variables in the guidelines for the application of nutrient solutions, there is no standard to measure it, not even to take a sample of it. Usually, drainage water is considered, or nutrient solution is extracted from the substrate [70]. With rockwool slabs this may be performed with the aid of a syringe [65], but neither a standard procedure is defined, nor the place and time for taking the sample outlined in corresponding recommendations. Sonneveld [66] suggested that the EC of the substrate be calculated as the mean EC of the supply and drainage solution. There are no reports in the literature of a unique relationship between the EC (and ion concentration) of the drainage water and that of the root zone. This lack of standardization is also a large handicap when building models and estimating parameters, and often prevents the use of data from different experiments to calibrate or validate a model.

It is likely that EC, water content and ion concentrations are not uniform in the root environment of substrate (and soil) systems [18, 33, 58, 79]. For example, De Rijck and Schrevens [15] measured ECs in the rockwool slab of a tomato crop of between 4.5 and 10 $dS \cdot m^{-1}$ for a supply EC of 2 $dS \cdot m^{-1}$, and Schwarz et al. [62] found, in a sand bed with lettuce, ECs of between 1.8 and 6.5 $dS \cdot m^{-1}$ for a supply EC of 2 $dS \cdot m^{-1}$. Sophisticated models that describe the root zone processes in detail have been used successfully to evaluate different irrigation and nutrition management strategies [e.g. 32, 33, 58]. For application in automatic control systems, these models are probably too complicated, and require the estimation of too many parameters specific to the system in use.

The plants themselves react to the different conditions in the root environment. On one hand, roots in good condition may compensate water and nutrient uptake for roots in bad condition [12]. A healthy plant reacts to the most favorable conditions in the root environment. Sonneveld and Voogt [69] grew tomato plants in a split root system and supplied nutrient solution of different concentration to the two halves of the root system. They found that yield was maximum when at least one half of the root system was exposed to optimal nutrient concentrations (EC at 2.5–3.0 $dS \cdot m^{-1}$). In addition, most of the nutrients were absorbed by the root half exposed to high nutrient solution concentration, while most of the water was taken up by the other half. Similar results were obtained by Sonneveld and De Kreij [67] with the cucumber. On the other hand, plants will restrict root growth into areas where conditions are unfavorable. Schwarz et al. [62] reported a negative correlation between root development expressed as root length density, and the local electrical conductivity in the root zone, for lettuce grown in sand beds.

Furthermore, plants do not respond to the long-term average of nutrient solution concentration. Adams and Ho [2] and Van Ieperen [77] found that the nutrient solution concentration during the day determined plant response while the concentration during the night could be neglected.

All the above underlines the difficulties of using nutrient solution concentration in the root environment as a target value for (automatic) control: water and nutrients are unevenly distributed in the root environment and, therefore, the concentration of the drainage water may not adequately characterize the conditions in the root environment. Furthermore, the effects of the plants vary widely because of the enormous capacity of plants for selecting ions [74]. For example, decreases in yield induced by salinity were reported for tomatoes to range from 2.3 to 9.9% per $dS \cdot m^{-1}$ of increasing EC of the nutrient solution in the root environment [55, 66].

It is also probably why sophisticated control strategies were not developed for free drainage systems. However, large amounts of nutrients leave the system with the drainage water, and nutrient use efficiency (*NUE*) is very low. From the data of Table II, mean nutrient use efficiencies may be calculated as

$$NUE = \frac{\left(1 - LF\right) C_u}{C_s}$$

for nitrogen at 0.45, for phosphorus at 0.62, for sulphur at 0.22, for potassium at 0.49, for calcium at 0.36 and for magnesium at 0.32. These ratios are similar to nutrient use efficiencies of soil systems [66]. Similar results were obtained with other greenhouse crops (not shown). When the nutrient concentration in the root environment is increased to improve product quality [19], nutrient use efficiency decreases further.

Table II. EC ($dS \cdot m^{-1}$) and element concentrations ($mmol \cdot l^{-1}$) in different parts of a tomato rockwool system for mean and maximum ratio of nutrient to water uptake at a leaching fraction (*LF*) of 0.3. Data sources:
Nutrient concentration in supply (C_s) and root environment (C_r) - Sonneveld and Straver [68], p. 22, mean nutrient to water uptake ratios (mean C_u) – Sonneveld [66], p. 95, maximum nutrient to water uptake ratios (max C_u) – derived from Voogt [81], mean and minimal nutrient concentration in the drainage water (C_d) – calculated using mean C_u and maximum C_u as $C_d = \frac{C_s - \left(1 - LF\right) C_u}{LF}$.
The EC is calculated analogously.

Element	C_s	Mean C_u	Max C_u	Mean C_d	Min C_d	C_r
N	15.00	9.6	20.0	27.6	3.3	17.0
P	1.25	1.1	4.7	1.6	–6.8*	0.7
S	3.75	1.2	3.5	9.7	4.3	5.0
K	8.75	6.1	11.0	14.9	3.5	7.0
Ca	4.25	2.2	4.7	9.0	3.2	7.0
Mg	2.00	0.9	1.5	4.6	3.2	3.5
EC	2.30	1.5	–	4.2	–	3.0

* A negative value for C_d is calculated; in practice it is not possible and means that for given C_s and *LF*, the potential uptake of this element is higher than the supply.

3.3. Reuse of the drainage water

3.3.1. Application of standard nutrient solutions

In progressive horticulture, drainage water is reused to save both water and nutrients and to avoid contamination of the ground water by fertilizer and other agrochemicals. In closed hydroponic systems, water and nutrients must be supplied in correspondence with their uptake [78], to prevent the occurrence of nutrient deficiencies or salinization [e.g. 7].

As in free drainage systems, water supply is controlled as a function of time and solar radiation by greenhouse computers. This is not sufficient in every situation as temperature and relative humidity may not have a negligible effect on transpiration. For example, Heißner [38] measured a doubling in water uptake of sweet pepper with increasing air temperature from 25 to 35 °C. One can easily calculate that the leaching fraction will decrease with increasing temperature, and consequently, the nutrient solution concentration of the drainage water and in the root environment increase [66]. Kläring et al. [49] reported an increase of the concentration of the drainage water in a tomato crop from 2.9 to 3.8 $dS \cdot m^{-1}$ within one week because of a decrease of the leaching fraction from 0.33 to 0.23. Irrigation was controlled by radiation only. There are many more sophisticated transpiration models and these could be included in control software. In practical applications, however, climate control and irrigation/nutrition control are often uncoupled. That means there is no definite assignment of the irrigation/nutrition units to the climate units in the greenhouses. Then, the indoor climate data is not available for irrigation and nutrition control. One possible solution could be the control of irrigation (and nutrition) based on measurements of outside weather data [8].

The amounts of supply water and drainage water can also be measured easily and used to readjust control parameters [11, 28]. Gieling et al. [27] proposed an approach to control the nutrient solution supply by sensor feedback of the measured drain flow, automatically compensating for fluctuations in evapotranspiration. Their approach is aimed at a constant drain flow, which is of interest with NFT. In substrate systems it is probably less practical because a constant drain flow has the unwanted consequence of strong diurnal fluctuations of the leaching fraction.

Compared to the water supply, the synchronization of nutrient demand by plants and nutrient supply is more complicated. When nutrient solutions of constant concentration are added to substrate systems, the concentration of the nutrient solution in the substrate varies. Variations occur because plants do not take up water and nutrients at a constant ratio. In horticultural production a constant total concentration controlled by electrical conductivity with variations in the ion ratio according to the growth stage of the crop is recommended for the root environment [13]. In practical applications, a more or less constant concentration in the root environment is achieved by reacting empirically to the electrical conductivity of the drainage water. This empirical feedback procedure requires expertise on the part of the grower because of the long and inconstant time lag between changes in the electrical conductivity of the nutrient solution supplied and of the drainage water [32, 50]. Conditions for nutrient and water uptake, e.g. the greenhouse climate, may also have changed considerably before changes to the input (supply concentration) can be measured at the output (drainage water concentration). The required composition of the nutrient solution should be checked frequently by the chemical analysis of samples in a laboratory. In the case of significant divergence from the required concentration, the compositions of the stock solutions must be changed. Of course, the time delay of a correction is immense when the flushing of the growth medium and discharge of the drainage water are not allowed.

3.3.2. Feedback control using ion sensitive measurements of the drainage water

Online measurements of different ions in the drainage water are applied to avoid unwanted variations in the concentration of the nutrient solution in the root environment [75]. Multihead injectors, for controlling the rates of addition of individual fertilizers, are a technical premise that allow for the adjustment of a large scale of nutrient compositions [5, 59]. A second technical premise needs further improvement; ion sensitive sensors are not available for all nutritional ions and are not robust enough against disruptive factors such as temperature variation, pollution or concentration changes of other ions [25, 35].

Nevertheless, strategies were developed that focused on an automatic control of the concentration of the nutrient solution, where the feedback of ion sensitive measurements is considered [3]. Young et al. [84] and Chotai and Young [10] proposed the application of the "True Digital Control" philosophy to NFT systems. They developed a self-adaptive control procedure for the nutrient solution concentration of a NFT system. Their results were based on theoretical studies, computer simulations and a small-scale physical model of a NFT flow system in a laboratory. The presented data was limited to one control variable (single-input single-output system). A similar approach was published by Gieling et al. [26], and aimed at the development of a multivariable controller for the application of water and eight macronutrients. As an example, it was shown in a simulation study that the controller could keep the amount of potassium returning from the plants at a constant level.

These feedback strategies deal with NFT systems. Probably, in substrate systems, the time delay between the control input and the feedback signal is too large for the application of these self-tuning strategies. For example, Heinen [32] showed that, for a sand bed system, a new solution of about 2 to 2.5 times the volume of the solution in the root zone must be added in order to remove most of the old solution. Similar results may be expected for other substrates. From the data of Table I one obtains for a rockwool system and a leaching fraction of 0.3 an average time delay for the replacement of the nutrient solution in the root environment of about 10 days. In all closed systems there is the additional problem that nutrients can be added to the solutions easily, but they cannot be removed to decrease their concentrations. They must be taken up by the plants. This, however, is a very slow process. Large storage systems for the drainage water must be available to enable the nutrient solution concentration to decrease more rapidly.

Moreover, it is often not reported how controllers deal with the ionic balance constraint in the nutrient solution. Heinen [31] included this constraint in a simulation study. He even used the ionic balance to calculate the non-measured concentration of the macronutrients magnesium and sulphur, from the measured concentration of the remaining anions and cations.

When experiments were carried out in greenhouses aimed at a constant nutrient composition, ion sensitive online measurements were often replaced by regular analyses of nutrient solutions in the laboratory [34, 57]. Special algorithms were developed to add single nutrients at the required ratios, which were calculated from measurements of the drainage water. Okuya and Okuya [57] used four and Heinen et al. [34] nine stock solutions, respectively. However, not every possible composition can be met exactly with the available stock solutions.

Brun et al. [9] proposed a feedback strategy that calculates the supply EC for the day based on the EC of the leachate solution and the greenhouse climate (air temperature) during the previous two days. In that way, they were able to maintain the EC of the leachate in a rose crop near the target value. As the control strategy was based on regression analysis, it is likely that it must be adapted to the system under consideration.

In many publications ion sensitive sensors are used to monitor the ion concentration in the nutrient solution and to estimate the nutrient uptake by plants [30, 56]. Approaches to an online control of the nutrient solution composition are, as outlined above, mostly on a theoretical level.

3.3.3. Feedforward control of nutrient solution concentration

A feedforward strategy to control the concentration of the nutrient solution was proposed by Kläring et al. [48]. They estimated the daily nutrient uptake using a model of net photosynthesis [36], assuming a constant nutrient content of the dry matter produced. The daily water uptake was estimated by a transpiration model [37]. Thus, the daily ratio of nutrient to water uptake was related to micrometeorological conditions in the greenhouse and could be used as a set point for the concentration of the nutrient solution supplied. A forecast of that ratio was used to adjust the nutrient solution concentration for the day on every morning [46]. This strategy was tested in greenhouse experiments with sweet pepper and tomato on rockwool, with the reuse of drainage water, and compared to the application of the standard nutrient solution [47]. The performance of the feedforward control was satisfactory and additional feedback control based on the concentration of the drainage water was not necessary. No effect on total yield of sweet pepper and tomato was found. However, there was a trend with both crops towards a reduced incidence of blossom-end rot compared to the standard, which focused on a constant nutrient solution concentration in the root environment [49]. The weak point of this approach is that the ratios of nutrient to water uptake are converted into an EC of the supply solution. Drainage water and stock solutions, however, have different ion compositions, but are mixed at changing ratios depending on the EC of the supply solution. This results in a variation of the nutrient solution composition. It is concluded that models for feedforward control have to consider varying ratios among the complemented nutrients.

Other authors prefer the addition of nutrients in correspondence with the expected growth and uptake rates [41]. One important argument is that maintaining high concentrations can result in excessive uptake, up to toxic concentrations, of some ions in the plants. Following their concept, water and nutrients are supplied together as nutrient solution, but in independent amounts [39]. This quantity concept yields excellent results in fundamental research under controlled environmental conditions. The plant can be maintained in a steady state, i.e. at a constant relative growth rate, a constant relative nutrient uptake rate and a constant internal element composition [42]. The nutrient solution is supplied in a very low concentration to control the exact addition rates of nutrients. Sufficient nutrient transport to the roots is achieved by very high flow rates of the nutrient solution in aeroponic or NFT systems [21]. This approach, in its purest sense of just adding the amounts needed to be taken up by the plants, is difficult to apply under practical grower conditions because:

- A crop cannot be maintained at a constant growth rate (steady state), the nutrient uptake rate and internal properties change with the growth stage and environmental conditions – these changes have high variations and are difficult to predict; and
- The required low nutrient solution concentrations and high flow rates are expensive to maintain in substrates due to the high cost of disinfection of the drainage water.

Therefore, only a few strategies based on the quantity concept have been published, aimed at applications in horticultural production. Schacht and Schenk [60] derived the nutrient uptake of cucumber from simulated plant growth. In a greenhouse experiment they added the nutrients in correspondence with the simulated nitrogen uptake, but corrected the model depending on results of weekly sap tests on leaf petioles. In a comparison to supply nutrient solution of constant concentration, they found no difference in nutrient uptake and yield [61]. Unfortunately, no details of the behavior of the control strategy, such as measured concentrations of the nutrient solutions or necessary model readjustments due to results of the sap test, were reported.

An approach to control water and nutrient supply using neural nets was presented by Honjo and Takakura [40]. From the input variables solar radiation, inside temperature, inside humidity, water temperature and CO_2 concentration, the output variables water supply and nutrient supply were identified. The nets were designed to learn the grower's strategy.

4. SUMMARY AND CONCLUSION

The use of information and models about the behavior of water and nutrients in the root environment and the responses of the plants would allow an improvement of present strategies to control water and nutrient supplies to greenhouse crops, and the move towards more environmentally friendly and economically optimal control strategies. However, many of these processes are poorly understood; for example, the plant response to the variation in space and time of water content and nutrient concentrations in the root environment. Moreover, the plant's response to the conditions in the root environment depends significantly on the greenhouse climate. Often, equal qualitative effects are obtained, but no unique quantitative relationships can be found.

Therefore, in practical application, the standard strategy for controlling nutrient and water supplies remains the application of standard nutrient solutions specific to the crop, and frequent analyses of samples of the nutrient solution in the root environment. Growers must adjust the settings and trajectories for irrigation and nutrition (EC, pH, ion composition) in accordance with the recommendations and their own observations on the status of the crop based on their experience. Due to the great ability of plants to adapt to different environmental conditions, this empirical strategy yields a high (although not optimal) production. It is a similar situation to that with the application of optimal greenhouse climate controls, where such efforts to develop optimal control strategies started at least 10 years earlier [80].

An improvement is expected by introducing a feedback control based on ion sensitive measurements of the concentration of the drainage water. It shows promise as an approach for NFT systems, but it remains questionable whether a pure feedback control would be successful with substrate systems. The long time delay in the system and the high buffering capacity of most growing media may be a problem to these controllers. Currently, the limited accuracy and long-term stability of ion sensitive sensors prevent their practical application.

Strategies based on the quantity concept are powerful tools in fundamental laboratory studies, but on an application level these strategies have rarely been undertaken. In greenhouse applications, feedback using measurements of water content and nutrient concentrations in the root environment or in the plant tissue is often needed to readjust the calculation procedures. The feedforward procedures for calculating the concentration of the nutrient solution supplied to the plants based on models of nutrient and water uptake will become of more practical relevance when the ion composition is included in the control strategy.

All current control strategies mainly consider the long-term nutrient and water uptake for monitoring plant nutrition. This is possible to a certain extent without reference to detailed physiological knowledge. On the other hand, crop models on nutrient uptake and the effect on plant growth and yield are still in the early stages of development [24]. Most studies develop functions on the response of crops to low ion concentrations, which limit the application in greenhouse production where there are high nutrient concentrations in the root environment [51]. Only recently, models have appeared that simulate the water or nutritional status of the crop and its effect on yield and product quality [23, 63, 64].

Current control strategies aim at a synchronization of nutrient and water uptake by plants, and nutrient and water supplies to the growing system. This approach is probably capable of handling the environmental aspect. The control of product quality, however, requires models that take into account plant functioning. This should encourage the development of irrigation and nutrition control.

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