CHAPTER

Hydroponic systems

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20.1 Introduction

Hydroponic systems are essential tools for plant production in indoor farming such as plant factories with artificial lighting (PFAL). Among various hydroponic systems, the deep flow technique (DFT), nutrient film technique (NFT), and aeroponic systems have been commercially used with recirculated nutrient solutions. Because ion concentrations in the nutrient solutions change with time causing a nutrient imbalance (Son and Takakura, 1987; Zekki et al., 1996; Cloutier et al., 1997), nutrient control systems with real-time measurements of all nutrients are required, but such systems are not yet available on a commercial basis. Instead, ion EC-based hydroponic systems have been the second-best choice but suffer from nutrient imbalance (Savvas and Manos, 1999; Ahn and Son, 2011). To improve the nutrient balance, periodical analysis of nutrient solutions and adjustment of nutrient ratios were conducted (Ko et al., 2013). As an advanced method, the ion-selective electrodes and artificial neural networks were used to estimate the concentration of each ion (Dorneanu et al., 2005; Gutierrez et al., 2007; Kim et al., 2013). To protect the plants in plant factories from disease, disinfection systems, such as ultraviolet (UV) systems, are required. The light intensity and exposure time of UV radiation are related with the disinfection ratio of pathogens (for example, Runia, 1995). This chapter describes the hydroponic systems, sensors and controllers, nutrient management systems, ion-specific nutrient management, and nutrient sterilization systems required for plant production in plant factories.

20.2 Hydroponic systems

A hydroponic system, or hydroponics, is a method of growing plants using mineral nutrient solutions in water without soil. For growing leafy vegetables in general, the main hydroponic systems used are the DFT and NFT systems. In the DFT system, nutrient solutions are supplied to the plants whenever the water level in the culture bed becomes lower than the set value, and are recirculated and supplied to the bare roots of plants, at constant time intervals, in the culture bed with a 1/100 slope. NFT systems and modified DFT systems similar to an ebb-and-flow system have been widely used in plant factories (Fig. 20.1).

In recirculation systems, nutrient solutions that are not absorbed by plants return to the nutrient tank. Therefore, water and nutrient absorption by plants can be easily estimated by measuring the loss

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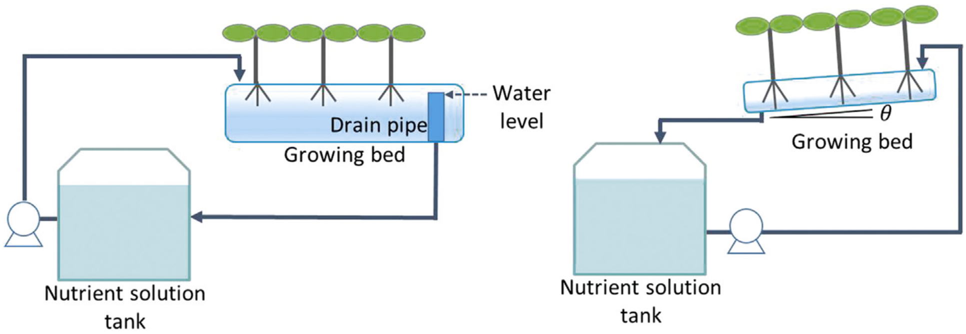

FIGURE 20.1

Schematic diagrams of DFT (left) and NFT (right) hydroponic systems.

of the nutrient solutions in the tank. In addition, aeroponic systems, which directly spray the nutrient solutions to the roots of the plants, also are used in plant factories.

20.3 Sensors and controllers

Root-zone environmental factors such as nutrient concentration, pH, dissolved oxygen, and temperature directly affect the growth of hydroponically grown plants. For real-time measurement of these factors, corresponding sensors are required. By assuming that the electric current increases with an increase of ionized nutrients in the nutrient solutions, electrical conductivity (EC) sensors are used to measure nutrient concentrations. Nutrient solutions absorbed by transpiration can be measured by water-level sensors in large nutrient solution tanks and by load cells in relatively small tanks. Ultrasonic wave or laser sensors can also be conveniently used for noncontact measurement of the water level in the tanks. The process of controlling the water and nutrient supplies is as follows: determine the amounts of stock nutrient solutions and water, inject them into the nutrient solution tank and mix them, and supply the mixed nutrient solutions to the plants. Nutrient control systems consisting of sensors and controllers are used commercially in hydroponic farms.

20.4 Nutrient management systems

20. 4.1 Open and closed hydroponic systems

Hydroponic nutrient solutions are composed of 13 essential elements. Each nutrient has a suitable concentration and relative ratios for the normal growth of a plant, and these are the target values of a nutrient control system. However, ionic concentration in the nutrient solutions changes with time, and subsequently a nutrient imbalance occurs in the closed hydroponic system (Fig. 20.2).

Thus, in order to achieve optimal control, all nutrients should be measured in real time. However, such a system has both economic and technical limitations. High-precision instrument analysis is relatively expensive, and ion sensors are still at the research stage for their durability and stability. To date, the field application of real-time measurement systems for individual nutrients is difficult;

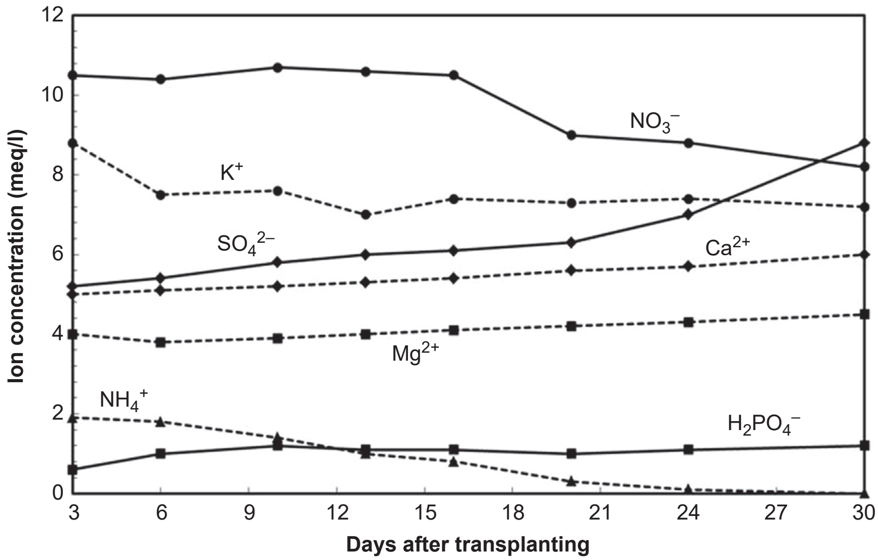

FIGURE 20.2

Changes in ionic concentration of the recirculated nutrient solutions controlled at a fixed EC (an example for lettuce).

instead, an EC and water-level sensor system for controlling total ion concentration is widely used. Closed systems that monitor the results of the control process are preferable for nutrient solution management (Fig. 20.3).

However, scaling-up the system requires a modular structure of the culture bed and drainage tank, and increasing the number of modules increases the installation cost. In contrast, open-loop control systems can have a relatively simple structure, even in the case of large-scale systems. But because they lack feedback, such systems might be inappropriate for plants which have higher fluctuations in uptake concentrations.

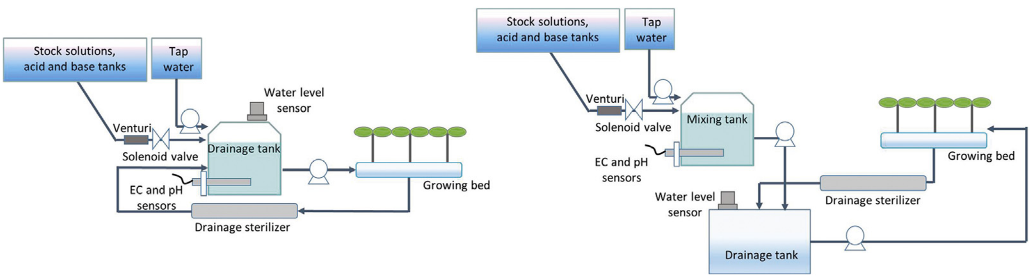

FIGURE 20.3

Schematic diagrams of closed (left) and open (right) hydroponic systems.

The concept behind EC-based hydroponic systems involves controlling total ion concentrations while minimizing nutrient imbalance through the injection of a stock solution. In order to operate the system normally, a theoretical understanding of the nutrient solution mixing procedure is required. The mixing process of nutrient solutions is discontinuously conducted by measuring changes in the amounts of nutrients and water in the drainage tank. This can be expressed as:

$$V_t\mathrm{EC}_t = V_c\mathrm{EC}_c + aU \; U = \frac{V_t\mathrm{EC_t} - V_c\mathrm{EC_c}}{a} \tag{20.1}$$

where V_t is the target volume of the nutrient solution stored in the drainage tank; $\mathrm{EC_t}$ is the target EC value (dS m^{-1}); V_c and $\mathrm{EC_c}$ represent the current volume of nutrient solution and EC in the drainage tank, respectively; U is the total amount of nutrients absorbed by the plants in milli-equivalent; and a is the empirical coefficient for conversion of total salt concentration and EC. For hydroponic solutions, a = 9.819 was suggested as the value of the coefficient by Savvas and Adamidis (1999), which can be in the range of 0.8–4.0 dS m^{-1}. Based on Eq. (20.1), the required injection amount of stock solution can be calculated by:

$$V_t\mathrm{EC}_t = V_c\mathrm{EC}_c + V_w\mathrm{EC_w} + V_{stk}\mathrm{EC}_{stk} \quad V_{stk} = \frac{V_t\mathrm{EC_t} - V_c\mathrm{EC_c} - V_w\mathrm{EC_w}}{\mathrm{EC_{stk}}} \tag{20.2}$$

where V_w is the required injection amount of tap water; $\mathrm{EC_w}$ is EC of tap water; V_{stk} is the required injection amount of stock solution; and $\mathrm{EC_{stk}}$ is the conversion of the milli-equivalent concentration of stock solution to EC. The sum of V_c, V_w, and V_{stk} should be equal to V_t. Therefore, from this relationship, the following equation can be derived:

$$V_{stk} = \frac{V_t\mathrm{EC_t} - V_c\mathrm{EC_c} - \mathrm{EC_w}(V_t - V_c)}{\mathrm{EC_{stk}} - \mathrm{EC_w}} \tag{20.3}$$

Once V_{stk} and V_w are calculated, these values are then submitted to the controller as reference input values, and actuators such as pumps and solenoids valves are activated.

20.4.2 Changes in nutrient balance under EC-based hydroponic systems

The transport of nutrients and water in the hydroponic system in Fig. 20.3 (left) can be expressed as a differential equation. Silberbush et al. (2001) constructed this model, and the above-mentioned EC-based nutrient solution mixing process is applicable in the model. The following equations are simplified models of nutrient and water transport in EC-based hydroponic systems.

$$V_b\frac{dC_b^i}{dt} = Q_{ir}C_{drg}^i - \frac{V_{max}C_b^i}{K_m + C_b^i} - (Q_{ir} - Q_{trs})C_b^i \tag{20.4}$$

$$V_{drg}\frac{dC_{drg}^i}{dt} = (Q_{ir} - Q_{trs})C_b^i + Q_{inj}C_{inj}^i + Q_{wtr}C_{wtr}^i - Q_{ir}C_{drg}^i \tag{20.5}$$

$$\frac{dV_b}{dt} = Q_{ir} - Q_{trs} - (Q_{ir} - Q_{trs}) \tag{20.6}$$

$$\frac{dV_{drg}}{dt} = (Q_{ir} - Q_{trs}) + Q_{inj} + Q_{wtr} - Q_{ir} \tag{20.7}$$

where V_b is the volume of the nutrient solution in the culture bed; V_{drg} is the stored nutrient solution in the drainage tank; C represents the concentration of individual nutrients, superscripts indicate the names of nutrients, and subscripts indicate the position of the nutrients; Q_{ir} is the irrigation rate; Q_{trs} is the transpiration rate; Q_{inj} is the stock solution injection rate; and Q_{wtr} is the tap water injection rate. Q_{inj} and Q_{wtr} are calculated by the above equation, and V_{max} and K_m are coefficients for Michaelis–Menten kinetics.

Based on this model, changes in nutrient concentration and balance under EC-based hydroponic systems can be simulated. Fig. 20.4 shows the simulated results of the changes in the concentrations and ratios of K^+, Ca^{2+}, Mg^{2+}, and Na^+. In practice, the absorption ratios between nutrients are not equal to the ratios in the nutrient solution, and therefore changes in the nutrient balance are observed during cultivation periods. The simulated results adequately show these tendencies. Nutrients which have relatively lower absorption rates such as Na^+ gradually increase in the nutrient solution. In EC-based hydroponic systems, the total ion concentration in the drainage tank is fixed at a target value; thus, it limits the injection amount of the stock solution. Therefore, the nutrient ratio of Na^+ in the nutrient solution rapidly increases, and this can result in a decrease of injection of other nutrients from the stock solution and lead to the development of salinity stress. However, if the tap water Na^+ concentration is in a certain range, the dynamic equilibrium can then be observed (Savvas et al., 2008). A major source of Na^+ inflow is tap water; therefore, the concentration at equilibrium is decided by the concentration in the tap water, the transpiration rate, and the absorption rate. If the predicted equilibrium concentration is above the threshold of a cultivated plant, then the application of a desalinator needs to be considered. Furthermore, ratios of other essential nutrients are important for normal plant growth, thus it is necessary to periodically analyze the nutrient solutions and adjust the nutrient ratios in the stock solution before deficiency or toxicity develops (Ko et al., 2013).

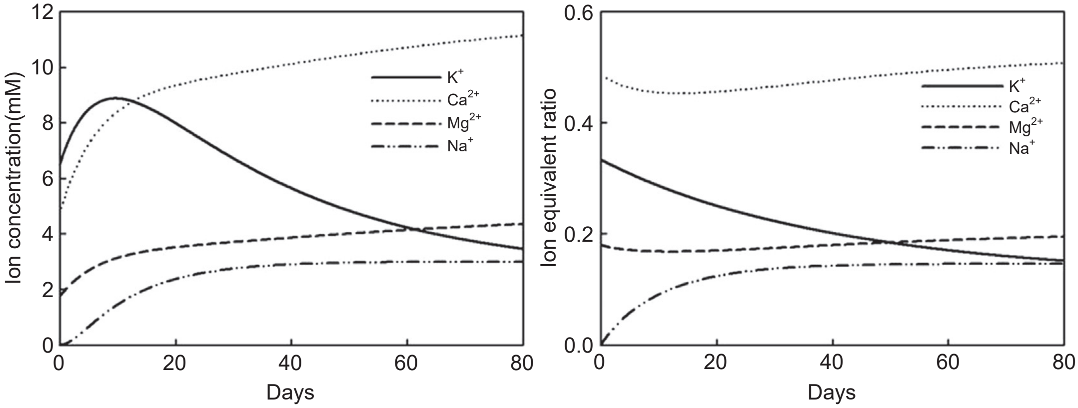

FIGURE 20.4

Simulated changes in the ion concentration (left) and the ion equivalent ratio (right) in the culture bed under an EC-based nutrient management system.

20.5 Ion-specific nutrient management

Hydroponic solutions contain various nutrients essential for crop growth. These nutrients are generally taken into plants in various ionic forms, such as NO_3^-, $H_2PO_4^-$, or HPO_4^{2-}, and K^+ through a combination of root interception and diffusion. Since the reserves of nutrients for the plants are limited in hydroponic greenhouse cultivation, an inaccurately balanced nutrient solution may result in an unbalanced nutrient composition in the root environment. In particular, deviations from the optimal concentration of any one ion can lead to the development of toxicity or deficiency symptoms and ultimately impair productivity (Bamsey et al., 2012).

In closed hydroponic systems that reuse the drainage solution, the build-up of salts is managed by dramatically reducing the fertilizers that are dissolved in the water, which are added to replenish the drainage solution (Fig. 20.5). However, in closed systems such as NFT, DFT, and ebb-flow systems, it is important to determine the nutrient concentrations in the reused solution to regenerate a nutrient solution of optimal composition because prolonged reuse of drainage water may lead to an accumulation of some nutrients, resulting in alterations in the nutrient ratios (Gutierrez et al., 2007).

To overcome such limitations regarding the use of closed systems on a practical scale, a feedback control loop that uses an ion analyzer is needed to dilute liquid fertilizers on the basis of on-line measurements of nutrient concentrations (Gieling et al., 2005). In addition, an algorithm implemented in a computer program is used to generate the time duration values needed to activate the valves for the addition of liquid fertilizer by the injection unit (Savvas and Manos, 1999). Current practices for managing hydroponic nutrients in closed systems are usually based on automatic control

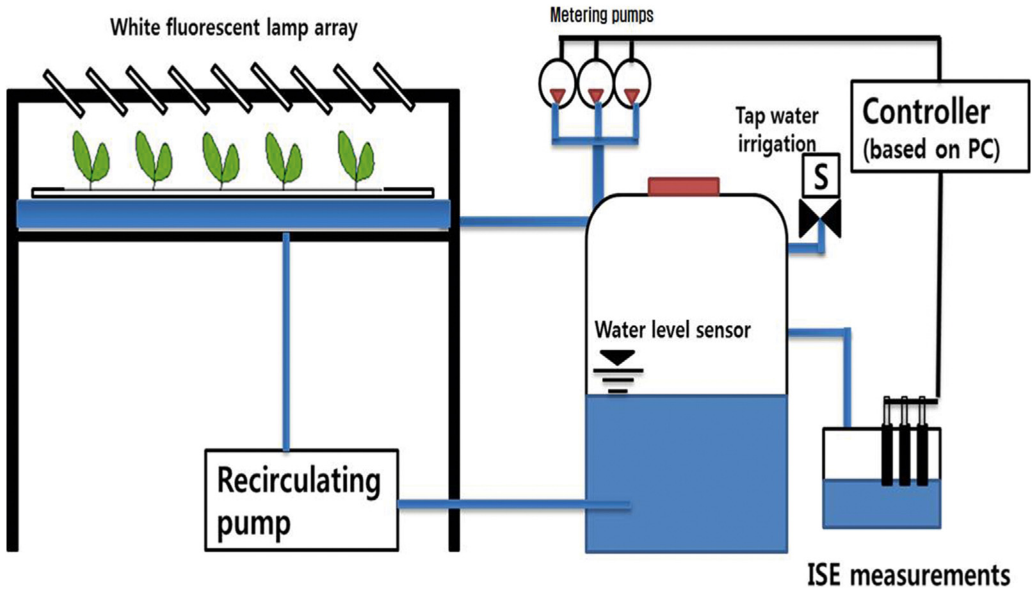

FIGURE 20.5

A schematic diagram of a closed hydroponic system based on nutrient feedback control.

of EC in the nutrient solution. A main problem with this practice is that EC measurements provide no information on the concentrations of individual ions and therefore do not allow individual real-time corrections to be made to each nutrient in response to the demand of the crop (Cloutier et al., 1997). Improved efficiency of fertilizer utilization may be possible through accurate measurement and control of the individual nutrients in the solution in real time.

The need for such fast, continuous monitoring has led to the application of ion-selective electrode (ISE) technology to measure hydroponic nutrients (Cloutier et al., 1997; Gutierrez et al., 2007). The advantages over standard analytical methods (spectroscopic techniques) include simple methodology, direct measurement, sensitivity over a wide concentration range, low cost, and portability (Heinen and Harmanny, 1992; Kim et al., 2013). The key component of an ISE is the ion-selective membrane that responds selectively to one ion in the presence of other ions in a solution. There are currently ion-selective membranes available for most of the important hydroponic nutrients, including NO_3^-, K^+, Ca^{2+}, and NH_4^+. However, there are several potential disadvantages of ion-selective electrodes as compared to standard analytical methods. One is chemical interference by other ions because ion-selective electrodes are not truly specific but rather respond more or less to a variety of interfering ions. To overcome interference issues, various data-processing methods such as multivariate calibration and artificial neural network (ANN) methods can be used. The multivariate calibration method is useful for allowing the cross responses arising from primary and interfering ions for accurately determining individual ion concentrations (Forster et al., 1991). An ANN method that uses data obtained with an array of multiple electrodes can be used for the simultaneous determination of various ions (Gutierrez et al., 2007). For example, as shown in Fig. 20.6, in a previous study that determined NH_4^+, K^+, Na^+, and NO_3^- ions in a hydroponic solution, the ANN was able to predict the concentrations of the tested ions with an acceptable level for almost 3 days without the need to remove the interfering effects.

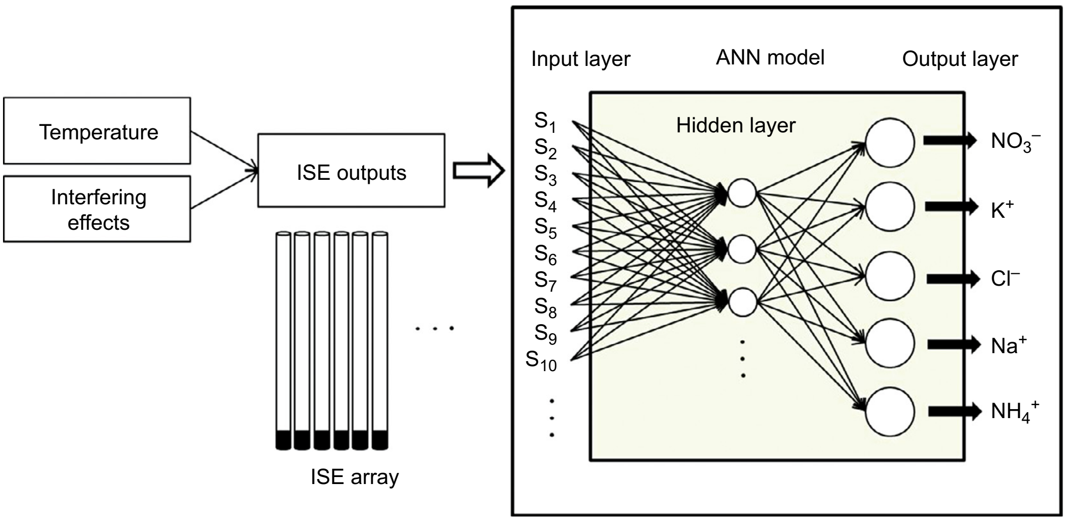

FIGURE 20.6

A schematic representation of the ANN method using an array of ion-selective electrodes.

Another disadvantage is reduced accuracy due to electrode response drift and biofilm accumulation caused by the presence of organic materials in hydroponic solutions (Carey and Riggan, 1994; Cloutier et al., 1997). In particular, stability and repeatability of the sensor response may be a major concern when considering an in-line management system that includes continuous immersion of ISEs in hydroponic solution because the accuracy of the measurement may be limited by the drift in electrode potential over time. The use of a computer-based automatic measurement system would improve the accuracy and precision of determining nutrient concentrations because consistent control of sample preparation, sensor calibration, and data collection can reduce variability among multiple electrodes during replicate measurements (Dorneanu et al., 2005; Kim et al., 2013). Ideally, an automated sensing system for hydroponic nutrients would be able to periodically calibrate and rinse the electrodes and continuously measure the nutrients in the hydroponic solution while automatically introducing solutions for calibration and rinsing as well as measurement. For example, in a previous study (Cho et al., 2018), a prototype of an on-site ion-monitoring system was developed to automatically measure the concentrations of three individual ions, i.e., NO_3^-, K^+, and Ca^{2+}, in hydroponic solutions (Fig. 20.7).

In closed soilless culture systems, the nutrient solution is usually prepared by fertilizer injection systems consisting of pumps and valves (Jung et al., 2015). The ratios are generally regulated by dispensing stock solutions according to real-time measurement of EC or nutrient concentrations to effectively achieve a preset value (Gieling et al., 2005; Savvas and Manos, 1999). A computer algorithm is used to calculate the amounts of stock solutions to be supplied and determine the time durations to activate the solenoid valves for the addition of fertilizers by the injection unit. The volumes of the nutrient stock solutions can be calculated simultaneously using a matrix equation (Jung et al., 2015) or separate calculations of the amounts of the individual nutrients to be replenished can be performed according to specific ions in a sequential order (Cho et al., 2017).

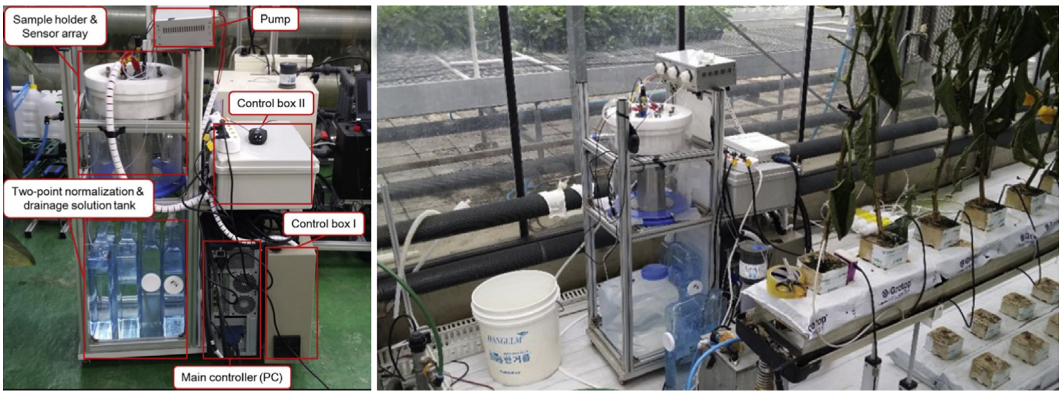

FIGURE 20.7

The hardware components of the prototype on-site ion-monitoring system (left) and a view of a greenhouse with the on-site ion monitoring system that monitors changes in hydroponic nutrients for paprika (right).

20.6 Sterilization systems

In general, contamination of crops by pathogens is lower in hydroponic cultures than in soil cultures; however, the pathogens can quickly spread to neighboring plants through the nutrient solutions when even one plant is contaminated. In order to minimize this risk, disinfection systems using filters, heat, ozone, and UV radiation are used in hydroponics.

Filtering systems eliminate the pathogens and other soluble solids in the nutrient solution, and their capacity is determined by pore size. Heating systems sterilize the pathogens by heating the nutrient solutions. Because the temperature for sterilization differs depending on the pathogen species, adequate ranges of temperatures should be set. After the heating treatment, a cooling process is required for reuse of the nutrient solutions on crops. Ozone (O_3) systems sterilize the nutrient solutions by using the oxidizing capacity of ozone gas. UV systems have the advantage of fast sterilization of pathogens in the nutrient solutions passing through the tube of the sterilizer. A light intensity of at least 250 mJ cm^{-2} is required to disinfect the pathogens perfectly (Runia, 1995). Even though the light intensity is within an adequate range, the sterilizing capacity decreases due to a lower transmittance of UV radiation if the turbidity of the nutrient solutions increases. To prevent this, filters should be installed in front of the UV sterilizer (Fig. 20.8). A disadvantage of UV systems is that the Fe-EDTA (chelating agent, ethylenediaminetetraacetic acid) in the nutrient solutions is precipitated and cannot be used. Therefore, addition of Fe-EDTA is required to compensate for the loss of Fe in hydroponic systems.

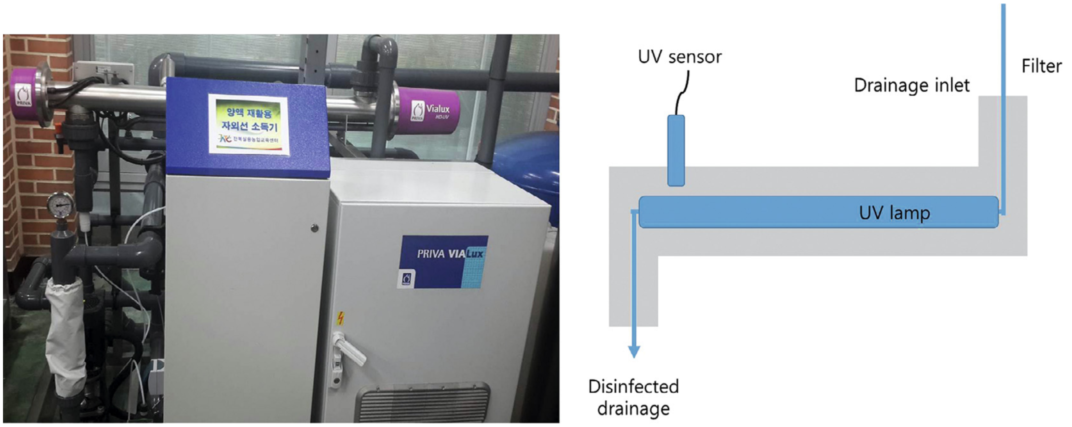

FIGURE 20.8

Commercial UV sterilizer (left, from the catalog of Priva) and schematic diagram of the structure (right).

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