Modelling of phosphorus accumulation in an aeroponic coriander crop

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Abstract: A model was developed for phosphorus (P) concentration over time in a closed aeroponic coriander culture. In addition, the setting and starting up of the soilless culture is described, and the measurements of electrical conductivity (EC), pH and concentration of major ions in the mixing tank are provided. By using mass balance principles, the dynamics of the nutrient concentration in the mixing tank and in the drainage solution are stated. Two series of continuous stirred tank reactors are considered for the flow structure, using a power law relationship to represent the rate of nutrient removal, considering water volume changes. Phosphorus concentration measurements were used for model fitting, and the resulting simulation is in good agreement with data.

Keywords: aeroponic culture, hydroponics, soilless culture, nutrient modelling, *Coriander sativum*

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1 Introduction

Hydroponic systems allow increased food production and reduced land requirement, consumption of water and nutrients, and harvest time. In turn, this contributes to tackle the increasing food demand resulting from continuous growth of world population[1-3].

Closed loop hydroponics lead to significant reduction of fertilizer and water consumption and groundwater pollution, which is associated to zero discharge of nutrient solution to the environment. However, long-term recycling of the drainage water results in the accumulation of nutrient ions (eg. Na^+ and Cl^-) in the plant root zone and in the recycled nutrient solution. Thus, the quality and quantity of crop growth are significantly affected. Indeed, crop yield decreases if either the electrical conductivity (EC) or the concentration of potentially toxic ions is higher than a threshold value. For instance, the threshold value of Na^+ concentration for tomato is 8 mol/m^3[4]. To avoid toxic ion levels in the rhizosphere, nutrient solution must be partially replaced when the electrical conductivity and/or the concentration of potentially toxic ions reach the threshold value. The term ‘semi-closed’ is used for these systems[5,6]. In turn, this discharge reduces the aforementioned benefits of closed loop hydroponics[4].

Automatic monitoring and control of nutrient solution leads to improved crop quality, reduction of manpower, and reduction of consumption and flushing of nutrient solution[4,7,8]. Automation can be used for pH control, nutrient solution supply (fertigation), control of nutrient solution concentration, and flushing of nutrient solution[9]. In particular, fertigation automatic control comprises management of the frequency of application of nutrient solution, and it provides the following advantages: i) unnecessary application of nutrient solution is reduced, and consequently the consumption of fertilizer and water resources is also reduced; ii) plant water stress related to water demand is reduced[10]; iii) discharge of drainage water is reduced[4].

In studies on automation of nutrient solution management, the control strategies are usually based on mathematical models, with monitoring of the electrical conductivity, individual ion concentration and pH[10]. Indeed, nutrient models provide information on crop-water requirements and can be used for fertigation management[11]. In particular, mass balance based modeling facilitates to account for several process units, fluxes and transformation mechanisms, as deduced from[12-14].

In this paper, a simple mass balance based modeling is performed for the time course of nutrient concentration in a closed aeroponic coriander crop. In addition, the setting and starting up of the soilless culture is described, and the measurements of electrical conductivity (EC), pH and concentration of major ions in the mixing tank are provided. The model was developed via mass balance principles, and it was fitted on the measurements of phosphorus concentration over time. The main contributions over closely related works are: i) the detailed application of the mass balance principles is provided, which allows further extension of the model in order to account for other fluxes or transformation mechanisms; ii) the mixing tank is considered as a different process unit, and the differential equation of its concentration is stated, accounting for the time varying volume.

The paper is organized as follows. The methods are described in section 3, including the hydroponic system, the irrigation cycles, the plant growth stage, and the measurement stage.

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The model development and fitting are presented in section 4. Finally, the discussion is presented in section 5 and the conclusions are drawn in section 6.

2 Preliminaries

Coriander (Coriandrum sativum) is widely used because of its flavor, nutritional and medicinal properties[15-18].

Coriander soil culture is typically found in tropical and mountainous zones as in the study place, achieving 40 to 60 cm height in approximately 60 d. Also, coriander can be grown in aeroponic systems[3,19].

2.1 Survey of mechanisms and modeling of P removal

The nutrient models allow scaling up hydroponic pilot systems to full-scale hypothetical systems intended for small communities. In the nutrient model in literature [20], the phosphorus concentration was considered as the limiting component that shows the effect of the water concentration on plant production.

In hydroponic cultures, the nutrient changes depend on plant age, nutrient concentration and number of plants. In particular, phosphorus (P) is removed by plant uptake and surface sorption (adsorption), but majorly by adsorption. The percentage of P removed through plant uptake decreases with water concentration. The presumed reason is that the more concentrated water implies a toxic effect that suppresses the growth potential of plants[20].

In the plant uptake process, P is absorbed via root uptake and then it is conveyed to plant tissues. Plant uptake depends on the age of plants and P concentration. In the surface sorption process, P moves

towards the surfaces of plant roots and other system surfaces. In the study [20], the majority of surface sorption occurred within the root mat. Also, it was observed that sorption to root surfaces decreases with time, which indicates saturation of the P binding sites. In the nutrient model proposed in literature [21], the rate of nutrient uptake is represented through an empirical relationship. An average constant nutrient flow rate is considered in the mass balance, despite the nutrient flow rates are different between irrigation and resting moments.

3 Materials and methods

The aeroponic culture was performed in a 120 m^2 greenhouse at Universidad Nacional de Colombia, Medellin, Colombia. The city is at 1479 elevation, with a constant subtropical climate during the whole year, and absolute temperatures ranging between 16.9 ° and 27.6 ° Celsius. Previous research on aeroponic culture in this greenhouse is described in [3, 19].

3.1 Hydroponic system and irrigation cycles

The hydroponic system consisted of: i) the cultivation bed, which is 6.0 m in length and 1.0 m in width (Figure 1); ii) three pipes of half an inch and 5.8 m long each; iii) 24 micro sprinklers of 180 ° with irrigation capacity of 26.0 L/h and 12 micro sprinklers of 360 ° with irrigation capacity of 26.0 L/h; iv) a motor pump (Pearl PSP 05, 373 W, 110 VAC) for nutrient solution supply; v) a storage tank of 130 L; vi) a collection channel covered with black polyethylene sheets, below the cultivation beds (see Figure 1c); vii) the electric system, involving a continuous power supply and a dsPIC (see Figure 2).

The nutrient solution was pumped and recycled according to the following irrigation cycles. At the start, the storage tank contained fresh nutrient solution. During the irrigation events, a fraction of the nutrient solution was pumped from the storage tank with a flow rate of 3000 L/h and sprayed to the plant root surface. The drainage water was conveyed by the collecting channel to the storage tank, where it was mixed with the remaining nutrient solution. Each of the pumping events lasted 20 s, followed by a rest period of 160 s. The cycles of nutrient solution irrigation were triggered by the electric system, involving a continuous power supply and a dsPIC that performs the automatic control of the cycles (see Figure 2 and Appendix A1, A2, A3). The irrigation cycles were applied during both the plant growth and the measurement stages, as is detailed in follows. The nutrient solution was prepared using the composition described in literatures [22,23]. The concentration of nutrients in parts per million (ppm) in this solution was N = 250.81, P = 25.64, K = 278.82, Ca = 157.20, Mg = 35.64, S = 81.20, Fe = 4.02, Mn = 0.74, Cu = 0.25, Zn = 0.57, B = 0.55 and Mo = 0.03.

a. Length side of the cultivation bed b. Width side of the cultivation bed

c. Collecting channel d. Cultivation beds with coriander root and shoot systems

Figure 1 Aeroponic system with coriander plants after 42 d under nutrient solution

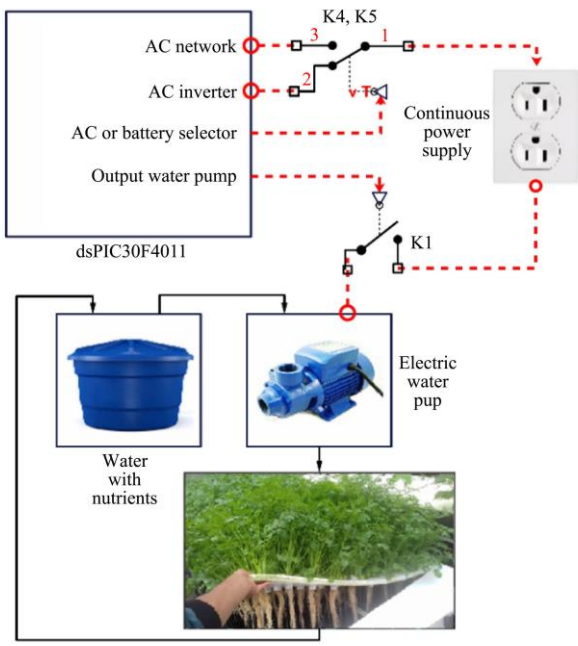


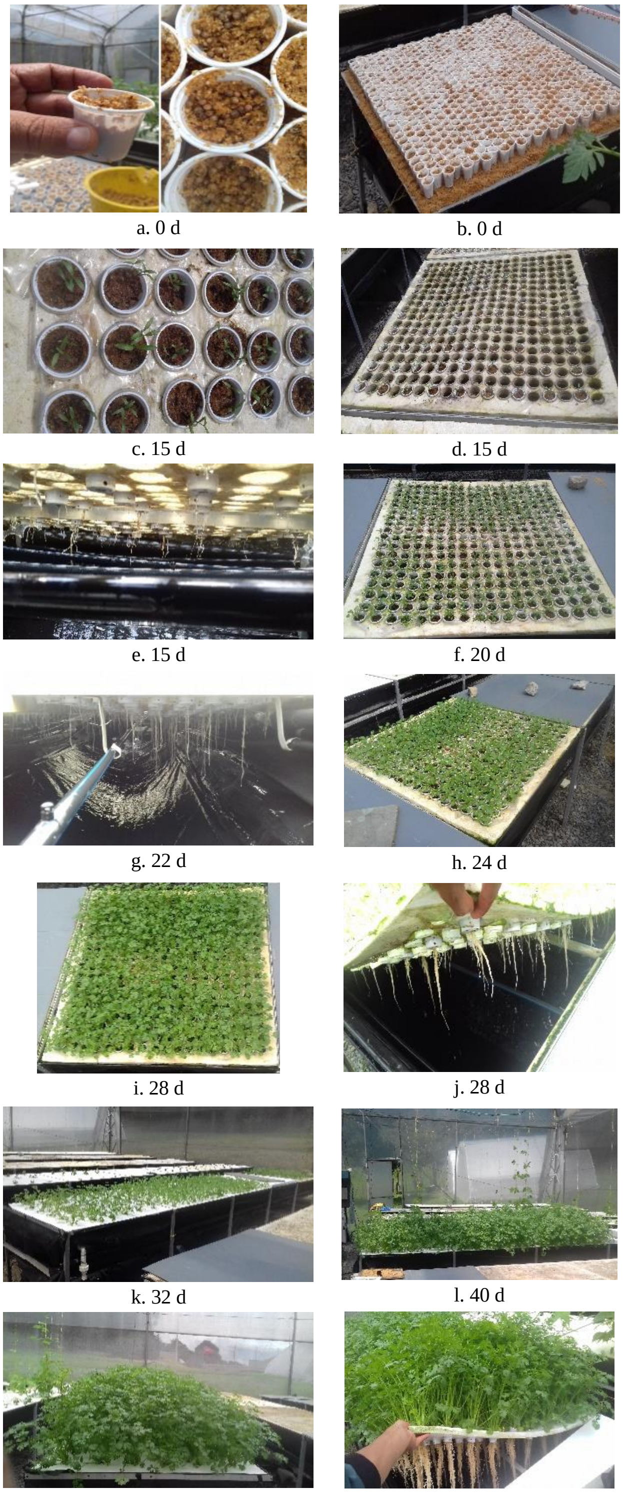
Figure 2 The electrical system, water pump, storage tank and cultivation bed

3.2 Plant growth stage

At first, coriander seeds were sown in wet sawdust in 2 cm diameter plastic cups to facilitate germination (see Figure 3). After a week, coriander seedling cups were transferred randomly to a final position in the bed. Next, plants were nourished with the complete nutrient solution for 42 d by applying irrigation cycles, with adjustment of pH within 5.5 and 6.5. The plant growth is shown in Figure 4. The final plants (Figure 1) have 40 cm of average length.

a. Coriander seeds in sawdust b. Cultivation beds with plastic cups

Figure 3 Growth of coriander plants



a. 0 d b. 0 d c. 15 d d. 15 d e. 15 d f. 20 d g. 22 d h. 24 d i. 28 d j. 28 d k. 32 d l. 40 d m. 42 d n. 42 d

Figure 4 Growth of coriander plants in the cultivation beds after seeding

3.3 Measurement stage

During the measurement stage, closed loop irrigation cycles were applied, following the aforementioned irrigation strategy, so that nutrient solution was neither replaced nor flushed nor adjusted, and pH was not modified. Samples of nutrient solution were collected from the storage tank, 0 d, 2 d, 4 d and 6 d after the start of the water cycle experiment.

The electrical conductivity (EC), pH, sodium ion (Na^+), magnesium ion (Mg^{2+}), potassium ion (K^+) were determined by NTC methods: NTC 5596-2008 (EC) [24]; NTC 3651-2012 (pH)[25]; NTC 4124 - 1997 (Na^+)[26]; NTC 5349-2016 (Mg^{2+})[27]; and NTC 5349-2016 (K^+)[27]. Chloride ion (Cl^-) was determined according to soil analysis reference methods[28], whereas calcium ion (Ca^{2+}) and phosphorus (P) were determined by validated methods of the Chemical Analysis Laboratory of the Universidad Nacional de Colombia (Medellin, Colombia).

3.4 Model development

The nutrient concentration model was developed via mass balance principles, considering two series of continuous stirred tank reactors (CSTR) for the flow structure, using a power law relationship to represent the rate of nutrient concentration changes. The model was fitted on phosphorus concentration measurements, by minimization of the simulation errors.

4 Results

The measurements of pH, EC and nutrient ions over time obtained in the measurement stage are shown in Figure 5.

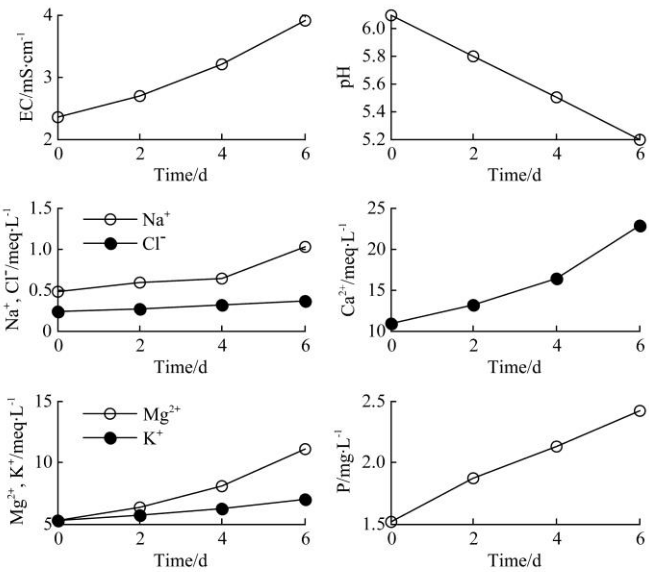


Figure 5 Time course of pH, EC and Na^+, Cl^-, Ca^{2+}, Mg^{2+}, P, K^+ in the closed aeroponic system

4.1 Development of the mass balance model

The system considered for modeling comprises the storage tank, plants, and nutrient solution. There are no nutrient flows between the outside and the inside of the system. It was assumed that the system can be represented by two linked CSTR (Figure 6), and the phosphorus (P) was selected as the limiting component that represents the transformation of nutrients.

The upper tank corresponds to the plants and the nutrient solution that drains from the plant roots. The lower tank corresponds to the nutrient solution in the storage tank. The notation used is: P_i, the phosphorus (P) concentration in the lower CSTR; P_e, the P concentration in the upper CSTR (outlet concentration); V_u, the water volume of the upper CSTR; r_u, the rate of P transformation via plant uptake and adsorption; Q_i the flowrate from the lower CSTR to the upper CSTR; Q_e the flowrate from the upper CSTR to the lower CSTR; Q_{ET}, the evapotranspiration rate; V_1, the water volume of the lower CSTR. The inflow of the lower tank (Q_e) is also the outflow of the upper CSTR, whereas the outflow of the lower tank (Q_i) is also the inflow of the upper CSTR (Figure 6).

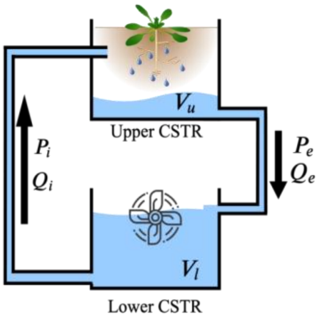


Figure 6 Structure of series continuous stirred tank reactors (CSTRs) used for the mass balance modeling

The upper tank exhibits water evapotranspiration and nutrient removal via sorption and plant uptake. The water volume V_u was assumed constant. Evapotranspiration and constant volume imply that the outflow (Q_e) is lower than the inflow (Q_i). The lower tank comprises mixing of the incoming water solution with that remaining. Therein, water evapotranspiration and nutrient removal were assumed negligible. The water volume (V_l) is continuously decreasing because the inflow (Q_e) is lower than the outflow (Q_i). The decreasing rate of the water volume ($C_v = \mathrm{d}V_l/\mathrm{d}t < 0$) was assumed constant. P_i increases with time, as indicated by experimental data; see Figure 5. Also, Na and Cl data are increasing with time. This increasing nature of concentration implies that the evapotranspiration effect is higher than that of the removal process.

The nutrient flow rates are different between irrigation and resting moments, which affects the P_i time course. Nevertheless, average constant flow rates (Q_i and Q_e) were considered in the mass balance. Such simplification was also undertaken in the modeling of literature [21]. In addition, the distribution of soluble and particulate phosphorus in water was assumed uniform, and root absorption of P was assumed to occur at the same time for all plants. Since the samples are taken from the lower CSTR, its concentration P_i is known, whereas the concentration of the upper CSTR (P_e) is unknown. So an empirical function was considered to represent the phosphorus removal rate.

The P mass balance statement for each control surface is [net P production or depletion rate] = [rate of P entering the control surface] – [rate of P leaving the control surface] – [rate of P removal via plant uptake and adsorption].

The P mass balance for the upper CSTR is:

$$\frac{\mathrm{d}(V_u P_e)}{\mathrm{d}t} = Q_i P_i - Q_e P_e - r_u V_u \qquad (1)$$

where, V_u is the water volume of the upper CSTR, L; Q_i is the flowrate from the lower CSTR to the upper CSTR, L/d; Q_e is the flowrate from the upper CSTR to the lower CSTR, L/d; P_e is the phosphorus concentration in the upper CSTR (outlet concentration), mg/L; P_i is the phosphorus concentration in the lower CSTR, mg/L. In addition, r_u is the rate of P removal via adsorption and plant uptake (mg/L·d), and is described via two empirical functions of the P_e concentration: $r_u = aP_e^b$, and $r_u = aP_e^b + c$, where a, b, c are constants to be estimated. The water balance for the upper CSTR is:

$$\frac{\mathrm{d}V_u}{\mathrm{d}t} = Q_i - Q_e - Q_{ET}$$

where, Q_{ET} (L/d) is the evapotranspiration rate. As V_u was assumed constant, then:

$$Q_i - Q_e - Q_{ET} = 0 \qquad (2)$$

and Equation (1) can be rewritten as:

$$\frac{\mathrm{d}(P_e)}{\mathrm{d}t} = \frac{Q_i}{V_u} P_i - \frac{Q_e}{V_u} P_e - r_u \qquad (3)$$

The P mass balance for the lower CSTR is:

$$\frac{\mathrm{d}(V_l P_i)}{\mathrm{d}t} = Q_e P_e - Q_i P_i \qquad (4)$$

where, V_1 (L) is the water volume of the lower CSTR. The water balance for lower CSTR is:

$$\frac{\mathrm{d}V_l}{\mathrm{d}t} = Q_e - Q_i \qquad (5)$$

where, $C_v = \mathrm{d}V_1/\mathrm{d}t$, which is negative and constant. The above expression leads to:

$$V_l = V_{lto} + (Q_e - Q_i)(t - t_0) \qquad (6)$$

where, V_{lto} is V_l at initial time t_0. Combining Equations (4) and (6) yields:

$$\frac{\mathrm{d}(P_i)}{\mathrm{d}t} = \frac{Q_e}{V_l}(P_e - P_i) \qquad (7)$$

In summary, the system is described by Equations (3), (6), (7). Arranging, one obtains:

Lower CSTR:
$$\frac{\mathrm{d}(P_i)}{\mathrm{d}t} = \frac{Q_e / |C_v|}{\frac{V_{lto}}{|C_v|} + (-1)(t - t_0)}(P_e - P_i) \qquad (8)$$

Upper CSTR:
$$\frac{\mathrm{d}(P_e)}{\mathrm{d}t} = \frac{Q_i}{V_u} P_i - \frac{Q_e}{V_u} P_e - r_u \qquad (9)$$

$$r_u = \{aP_e^b \text{ or } aP_e^b + c\} \qquad (10)$$

4.2 Model fitting

Model simulation and fitting were performed on Equations (8)-(10), using MATLAB software. The differential equations were solved by using the Ode45 command. The model parameters were fitted via minimization of the squares of the errors between the experimental and simulated values of P_i. The goodness of fit was evaluated by means of the R^2 value[29,30].

The experimental points and the simulated time course of the P concentration are shown in Figures 7 and 8.

For the model with $r_u = aP_e^b$ the estimated parameters are: $Q_e/|C_v| = 2960$; $V_{to}/|C_v| = 36000$ d; $Q_i/V_u = 117.1$ d^{-1}; $Q_e/V_u = 20.39$ d^{-1}, $a = 15.99$ (mg/L)$^{1-b}$d^{-1}; $b = 1.672$; and $R^2 = 0.990$.

The R^2 value and Figs. 7 and 8 show that the model achieved a satisfactory description of the measured time course of phosphorus concentration.

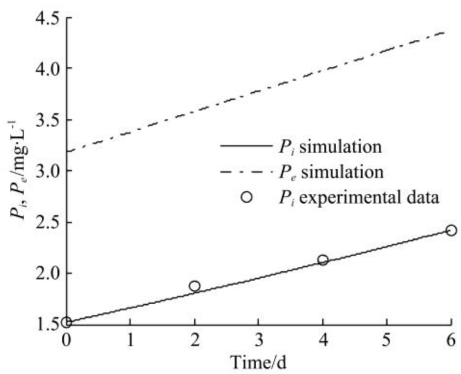


Figure 7 Fitting of P model, using $r_u = aP_e^b$

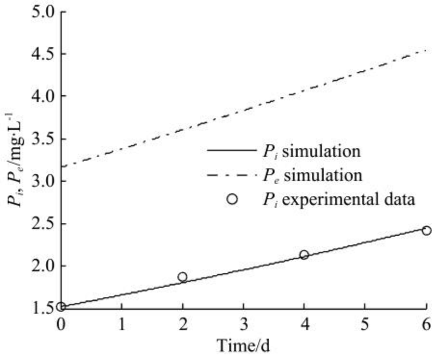


Figure 8 Fitting of P model, using $r_u = aP_e^b + c$

5 Discussion

The concentrations of Na^+, Cl^-, Ca^{2+}, Mg^{2+}, PO_4^{3-}, K^+, and the EC increased with time during the six days of the measurement stage, which is in agreement with the salt build up pattern of the closed loop irrigation cycles for different crop species, for instance, tomato[4] and pepper[31].

The obtained R^2 values imply that the power law $r_u = aP_e^b$ expression of the removal rate and the assumed model structure based on two CSTRs with flow exchange and the considered assumptions are adequate for the working aeroponic culture.

The model simulation and calibration are simple, as it involves a low number of parameters to estimate. It can be applied to other aeroponic culture, with other climatic conditions (temperature and radiation), nutrient solution composition and pH, type of growing media, plant species, vegetative stage of growth.

Also, the model development can be improved by using a more realistic representation of the nutrient and water uptake by plants, and by incorporating: i) the effect of temperature on the water volume and nutrient removal rate; ii) the effect of water transpiration on the water volume; iii) the time varying nature of the outlet and inlet flows of the mixing tank (irrigation and drainage flows); iv) the use of flushing of the nutrient solution; v) the addition of fresh nutrient solution, including nutrient concentration and volume added; vi) water losses in the mixing tank.

Also, an improved calibration for that improved model would comprise: i) using measurements corresponding to several periods of addition of fresh nutrient solution, and several concentrations of the added nutrient solution; ii) performing different calibrations for the seasons of the year; iii) using measurements of the concentration of the drainage solution; iv) using measurements of the mixing tank volume, which is time varying; v) using measurements of the flows of the irrigation water and drainage water, which are not constant.

6 Conclusions

The time course of the electrical conductivity (EC) and the concentration of major ions (Na^+, Cl^-, Ca^{2+}, Mg^{2+}, P, K^+) in the mixing tank was increasing, whereas the pH is decreasing; this agrees with current trend in closed loop hydroponic systems, associated to salt buildup.

The model achieved a satisfactory description of the measured time course of phosphorus concentration. This implies that the assumptions undertaken, including the model structure based on two CSTRs with flow exchange and a power type rate of mineral removal, are adequate. As the model is based on mass balance, it can be extended by incorporating different water and biological effects. Also, the calibration can be improved by using measurements of volumes, flows, and by considering different water and climatic conditions. That improved model would allow testing different control strategies, using the flow of fresh nutrient solution as control input, and electrical conductivity as output. Also, it would allow optimization by proving different strategies of application of fresh nutrient solution, with different times of application and different concentrations.

Appendix

The irrigation cycle module in the dsPIC30F4011 (Microchip Technology Inc.) starts the water pump, switching it ON for 20 s and OFF for 160 s. Furthermore, the power supply involves a sensor that measures the lack of electricity coming from the power grid.

The design of the electric system (see Appendix A1 to A3) includes the electrical circuit for power supply, the irrigation cycle, and the connection between the nutrient solution cycle and the power supply system.

A1. Automatic irrigation system

The sequence blocks were implemented in MATLAB-Simulink software. Figure A3 shows the module programed for the irrigation cycles of the aeroponic system. After some adjustments, the final program is downloaded to dsPIC and facilitates the control of the ignition and irrigation system of the motor pump. Furthermore, another block was program as a pulse generator, where the electrical water pump produces a PWM signal with ON for 20 s and OFF for 160 s. These times are set to provide nutrients to the plants by switching the micro sprinklers. The water pump is operated by the digital output of the B0 electric water pump, during which the valve must be turned off for 160 s to complete the irrigation cycle.

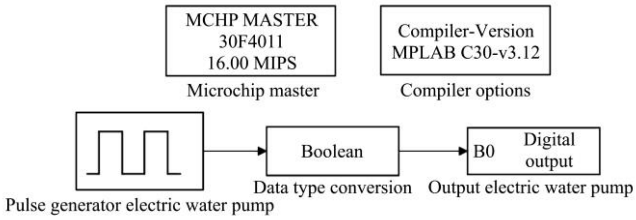


Figure A1 Irrigation cycle blocks[3]

A2. Electrical system

Figure A2 shows the diagram of the electrical circuit built with micro sprinklers and irrigation cycles. This electrical system was designed to provide all the nutrients to the plant. In this figure, the block marked with B0 is used to regulate K1 with the MOSFET IRFZ44N and starts the electric water pump.

A3. Power supply

Electricity supply is very important for the aeroponic food-producing systems because plants require waters and nutrients continually[32]. Thus, water pumps need energy to supply nutrients through micro sprinkler to plants. However, it is sometimes difficult to maintain a continuous electrical service because of disconnections in the power grid. If an electricity outage is presented for up to 5 hours, then plants enter in a lengthy process of tension due to water and nutrient shortages. Shortages of water and nutrients decrease contribute to death of plants.

Therefore, an auxiliary battery system was designed to supply electricity service for approximately 24 h. The system consists of two 12 VDC and 155 A·h batteries, a 3 kW DC-AC inverter, and an AC-DC battery adapter. Thus, the greenhouse is fed by batteries and mainly used for the aeroponic irrigation systems.

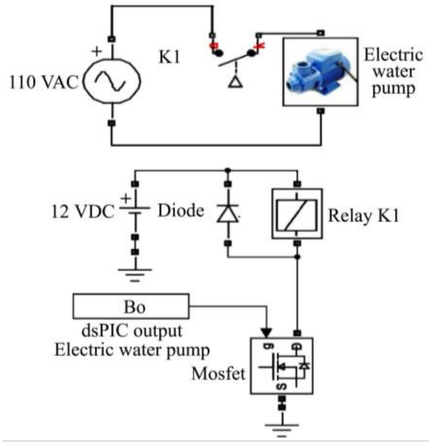


Figure A2 Diagram of the electric circuit[3]

The block diagram used to supply electricity for the aeroponic system is presented in Figure A3. These blocks were programmed in MATLAB-Simulink and implemented in dsPIC30F4011. The AC voltage input sensor helps identify the electricity absence of the power grid. The AC block triggers B3 output for the power grid or B4 output for batteries. The delay feature includes a time of millis to prevent the ON of all outputs B3 and B4 or the presentation of short-circuits in the circuit. The UART 2 block is located to display the real-time signal of the voltage sensor.

The electrical circuit for the complete system is shown in Figure A4. B3 input controls K4 which is responsible for [supplying electricity with the power grid. However, when the power grid is out of power, the B4 input controls K5 to feed electricity with the battery.

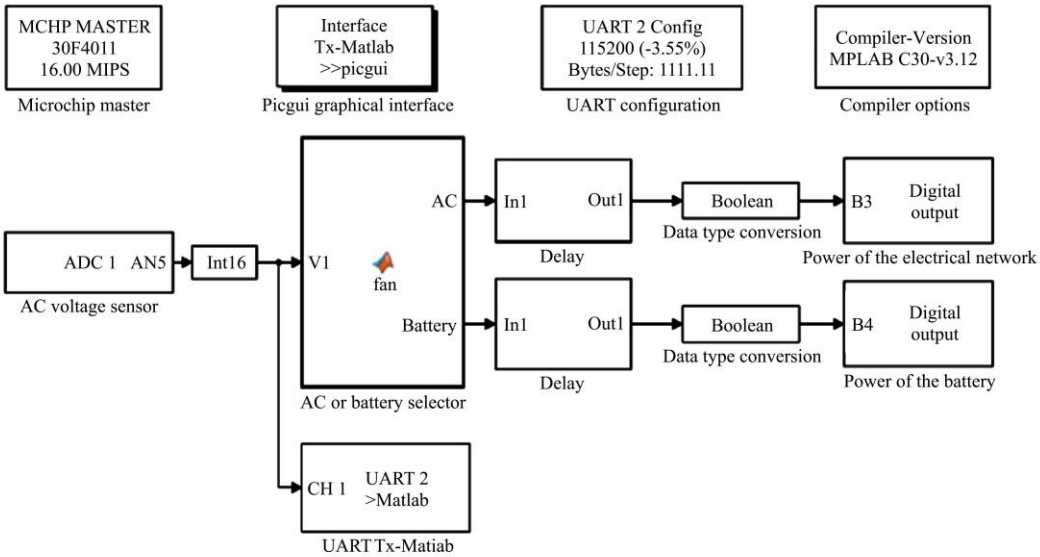


Figure A3 Power supply of the aeroponic system[3]

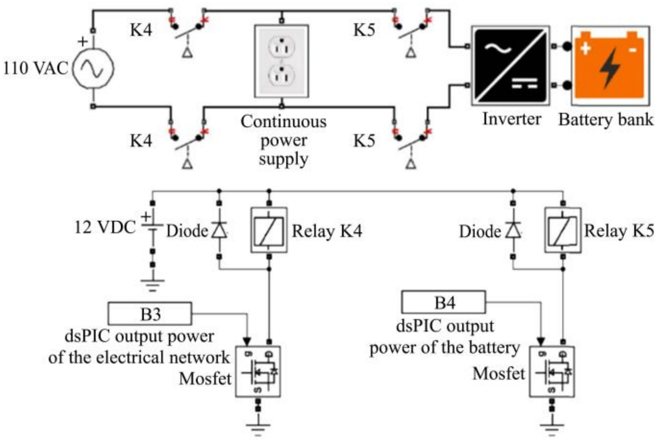


Figure A4 Electrical circuit designed for continuous power supply[3]

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[References]

[1] Odegard I Y R, van der Voet E. The future of food — Scenarios and the effect on natural resource use in agriculture in 2050. Ecological Economics, 2014; 97: 51–59.

[2] Runia W T. A review of possibilities for disinfection of recirculation water from soilless culture. Acta horticulturae, 1995; 382: 221–229.

[3] Hoyos Velasco F, Candelo J E, Chavarria H J. Automatización de cultivos aeropónicos de cilantro libres de pesticidas. INGE CUC, 2019; 15(1): 123–132.

[4] Varlagas H, Savvas D, Mouzakis G, Liotsos C, Karapanos I, Sigrimis N. Modelling uptake of Na^+ and Cl^- by tomato in closed-cycle cultivation systems as influenced by irrigation water salinity. Agricultural Water Management, 2010; 97(9): 1242–1250.

[5] Carmassi G, Incrocci L, Maggini R, Malorgio F, Tognoni F, Pardossi A. An aggregated model for water requirements of greenhouse tomato grown in closed rockwool culture with saline water. Agricultural Water Management, 2007; 88(1-3): 73–82.

[6] Massa D, Incrocci L, Maggini R, Bibbiani C, Carmassi G, Malorgio F, et al. Simulation of crop water and mineral relations in greenhouse soilless culture. Environmental Modelling & Software, 2011; 26(6): 711–722.

[7] Domingues D S, Takahashi H W, Camara C A P, Nixdorf S. Automated system developed to control pH and concentration of nutrient solution evaluated in hydroponic lettuce production. Computers and Electronics in Agriculture, vol. 2012; 84: 53–61.

[8] Pala M, Mizenko L, Mach M, Reed T. Aeroponic greenhouse as an autonomous system using intelligent space for agriculture robotics. Robot Intelligence Technology and Applications 2, 2014; pp.83–93. doi: 10.1007/978-3-319-05582-4_7.

[9] Palande V, Zaheer A, George K. Fully automated hydroponic system for indoor plant growth. Procedia Computer Science, 2018; 129: 482–488,

[10] Steidle Neto A J, Zolnier S, de Carvalho Lopes D. Development and evaluation of an automated system for fertigation control in soilless tomato production. Computers and Electronics in Agriculture, 2014; 103: 17–25.

[11] Carmassi G, Incrocci L, Maggini R, Malorgio F, Tognoni F, Pardossi A. Modeling salinity build-up in recirculating nutrient solution culture. Journal of Plant Nutrition, 2005; 28(3): 431–445.

[12] Silberbush M, Ben-Asher J. Simulation study of nutrient uptake by plants from soilless cultures as affected by salinity buildup and transpiration. Plant and Soil, 2001; 233(1): 59–69.

[13] Yang T, Kim H-J. Comparisons of nitrogen and phosphorus mass balance for tomato-, basil-, and lettuce-based aquaponic and hydroponic systems. Journal of Cleaner Production, 2020; 274: 122619. doi: 10.1016/j.jclepro.2020.122619.

[14] Keesman K J, Körner O, Wagner K, Urban J, Karimanzira D, Rauschenbach T, et al. Aquaponics systems modelling. in Aquaponics Food Production Systems. Springer, 2019; pp. 267–299. doi: 10.1007/978-3-030-15943-6_11.

[15] Björkman M, et al. Phytochemicals of Brassicaceae in plant protection and human health--influences of climate, environment and agronomic practice. Phytochemistry, 2011; 72(7): 538–556.

[16] Dekker M, Verkerk R. Dealing with variability in food production chains: A tool to enhance the sensitivity of epidemiological studies on phytochemicals. European Journal of Nutrition, 2003; 42(1): 67–72.

[17] Hayes J D, Kelleher M O, Eggleston I M. The cancer chemopreventive actions of phytochemicals derived from glucosinolates. European Journal of Nutrition, 2008; 47(SUPPL. 2): 73–88.

[18] Kumar S, Jawaid T, Dubey S. Therapeutic Plants of Ayurveda; A Review on Anticancer. Pharmacognosy Journal, 2011; 3(23): 1–11.

[19] Ríos Salazar J D, Candelo-Becerra J E, Hoyos Velasco F E. Growing arugula plants using aeroponic culture with an automated irrigation system. Int J Agric & Biol Eng, 2020; 13(3): 52–56.

[20] Rababah A A, Ashbolt N J. Innovative production treatment hydroponic farm for primary municipal sewage utilization. Water Research, 2000; 34(3): 825–834.

[21] Savvas D, Meletiou G, Margariti S, Tsirogiannis I, Kotsiras A. Modeling the relationship between water uptake by cucumber and NaCl accumulation in a closed hydroponic system. HortScience, 2005; 40(3): 802–807.

[22] Hoagland D R, Arnon D I. The water-culture method for growing plants without soil. Circular. California Agricultural Experiment Station, 1950; 347. 2nd edit.

[23] Taiz L, Zeiger E. Plant physiology. Fifth Edition. Sinauer Associates, Inc., 2010. Available: https://www.amazon.com/-/es/Lincoln-Taiz/dp/0878938664. Accessed at [2020-12-10].

[24] ICONTEC. NTC 5596-2008. Soil quality. Determination of electrical conductivity, 2008.

[25] ICONTEC. NTC 3651-2012. Water quality. Determination of pH. 2012.

[26] ICONTEC. NTC 4124-1997. Environmental management. Water quality. Determination of sodium and potassium. Determination of sodium by atomic absorption spectrometry, 1997.

[27] ICONTEC. NTC 5349-2016. Soil quality: Determination of exchangeable bases. Method of extraction using ammonium acetate 1N and pH 7, 2016.

[28] Soil and Plant Analysis Council Inc. Soil analysis handbook of reference methods. CRC-Press, 2000.

[29] Motulsky H, Christopoulos A. Fitting models to biological data using linear and nonlinear regression: A practical guide to curve fitting contents at a glance. San Diego, CA, USA: GraphPad Software Inc., 2003.

[30] Mayo A W, Muraza M, Norbert J. Modelling nitrogen transformation and removal in mara river basin wetlands upstream of lake Victoria. Physics and Chemistry of the Earth, Parts A/B/C, 2018; 105: 136–146.

[31] Savvas D, Chatzieustratiou E, Pervolaraki G, Gizas G, Sigrimis N. Modelling Na and Cl concentrations in the recycling nutrient solution of a closed-cycle pepper cultivation. Biosystems Engineering, 2008; 99(2): 282–291.

[32] NASA Spinoff. Progressive plant growing has business blooming. Environmental and Agricultural Resources, 2006. https://spinoff.nasa.gov/Spinoff2006/er_2.html.