Simulation study to assess the efficiency of the software NUTRISENSE to optimise nutrient supply using ion selective electrodes in closed-loop soilless cropping systems

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Abstract: A software used to control fertigation systems (FS) for automated preparation of nutrient solutions based on real time sensing of the drainage solution using ion selective electrodes (ISEs) was developed. This software, named NUTRISENSE, can be used to optimize recycling of the fertigation effluents in closed-loop soilless culture systems. The use of ISEs in conjunction with NUTRISENSE provides a tool to the growers to monitor in real time the fluctuations of major nutrient concentrations in the fertigation effluents, and supplement them with the appropriate amounts of fertilizers. This strategy improves the accuracy of the nutrient supply in closed-loop soilless culture systems. Thus, growers could be encouraged to switch to recycling of the fertigation effluents as the uncertainty in nutrient supply that discourages them from adopting closed-loop soilless cultivation systems would be lifted. This study provides an overview of algorithms used by NUTRISENSE to calculate the nutrient supply when the composition of major nutrients is monitored in real time using ion selective electrodes. Furthermore, a simulation study was conducted to assess the capabilities and the limits of the system and highlight the research needs for its application in greenhouse experiments.

Key-Words: Decision support system; greenhouse automation; hydroponics; ion selective electrodes; nutrient modeling

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List of symbols and abbreviations

Abbreviations
AS: added solution
CLS: Closed-loop soilless culture systems
DS: drainage solution
DSS: decision support system
ISE: ion selective electrode
NS: nutrient solution
SS: supply solution
SCS: soilless culture systems
UC: uptake concentrations
Symbols
C_a is the concentration (mM) of each nutrient in the AS
C_{ar} is the readjusted concentration (mM) of each nutrient in the AS,
C_d is the concentration (mM) of each nutrient in the DS.
C_i is the concentration of the *i* nutrient (*i* = K, Ca, Mg, NH_4-N, NO_3-N, SO_4-S, P, Fe, Mn, Zn, Cu, B, Mo, Cl) in any solution referenced in the paper,
C_m is the concentration (mM) of each nutrient in the blend of DS and raw water,
C_{nt} is the injection rate of each nutrient (mM),
C_s is the concentration (mM) of each nutrient in the SS,
C_{st} is the target concentration (mM) of each nutrient in the SS,
C_{sr} is the readjusted concentration (mM) of each nutrient in the SS,
C_u is the uptake concentration (mM) of each nutrient,
C_{ua} is the actual uptake concentration (mM) of each nutrient,
C_w is the concentration (mM) of each nutrient in raw water,
T_p is the application time (d) of the currently supplied AS (days from the n-1 to the n sampling of DS).
V_d is the volume sum (L) of root solution and drainage solution per plant,
V_a is the volume (L) of supplied AS per plant per day (net supply of NS excluding the resupply of DS),
E_a is the EC (dS m^{-1}) of the AS,
E_m is the EC (dS m^{-1}) of the blend of DS and raw water,
E_s is the target EC (dS m^{-1}) in the SS,
a is the target fraction of DS (referring to the total volume of SS) that is recycled.

1 Introduction

Soilless culture systems (SCS) constitute the dominant cultivation technique in greenhouse production units that use modern technology to achieve high yield per unit area. The main environmental advantage of SCS is the elimination of surface and underground water pollution due to nitrogen and phosphorus emissions originating from fertigation effluents. To minimize water contamination and make the greenhouse units more sustainable, closed-loop SCS have been developed, (henceforth abbreviated as CLS) where the fertigation effluents are collected and recycled. Moreover, the recycling of fertigation effluents, henceforth termed drainage solution (DS), reduces irrigation water and fertiliser consumption by more than 30% and 40%, respectively (Savvas and Gruda, 2018; Savvas et al. 2023). CLS are mandatory in northern European countries, such as The Netherlands to avoid water contamination (Voogt and Bar-Yosef, 2019). However, they are rarely used in southern European countries because of low-tech greenhouse facilities, high salinity of irrigation water and the uncertainty caused by the fluctuations of the nutrient concentrations in the recycled DS which in most cases cannot be efficiently managed due to insufficient availability of specialised advisory services locally. On the other hand, the limitations in water resources constitute a much bigger problem in the south-European compared to the north-European countries. Thus, switching to closed-loop soilless systems should be a priority in the greenhouses of south-European countries as well as in other countries with dry climates, due to the considerable water savings achieved by recycling the fertigation effluents. In many Mediterranean greenhouses, application of a fully closed soilless system with zero DS discharge is not possible due to moderately high Na concentrations in the available irrigation water. However, in these cases, application of a semi-closed system with periodic discharge of some DS could save considerable amounts of precious irrigation water, if suitable models are used to define the exact time, duration, and fraction of DS discharge (Katsoulas et al., 2015).

The management of plant mineral nutrition through the nutrient solution (NS) is one of the greatest challenges in CLS because the composition of the DS can vary with time as a result of temporal variations in nutrient uptake requirements. In these systems, it is necessary to monitor the mineral composition of the DS regularly for two main reasons. The first reason is the need for accurate preparation of the nutrient solution supplied to the crop, henceforth, supplied solution (SS). The second reason is the need to maintain optimal levels of nutrients, electrical conductivity (EC), and pH in the root environment, i.e., in the DS (Sonneveld and Voogt, 2009). The DS is mixed with a nutrient solution with a composition assumed to exactly match the plant uptake, henceforth termed added solution (AS), to obtain the SS. Hence, to achieve the target composition of the SS, the AS composition must be calculated taking into consideration the composition of the DS. Inappropriate composition of the SS can cause nutrient imbalances in the root environment, which may affect the plants through nutrient deficiency or toxicity, or salinity stress (Sonneveld and Voogt, 2009; Neocleous and Savvas, 2013; Tzerakis et al., 2013; Massa et al., 2020). The plant nutrient uptake can be expressed as the ratio between the absorbed nutrient mass and the absorbed volume of water, which is termed “uptake concentration” (UC) in the international scientific literature (Sonneveld and Voogt, 2009; Thompson et al., 2013, Block et al., 2023). The UC of each nutrient may fluctuate within a range during the cropping period, due to the plant developmental stage, changes in cropping conditions such as the microclimatic parameters, fruit load, etc., as these parameters could alter the nutrient needs of the plants (Gallardo et al., 2021). Therefore, the UC of the plants and concomitantly the composition of the SS should be periodically recalculated, based on analytical data of the DS, which is representative of the root solution composition (Sonneveld and Voogt, 2009), to adapt to current crop demands (Savvas et al., 2023).

To address these requirements, the decision support system (DSS) NUTRISENSE, has been developed by the Laboratory of Vegetable Production of the Agricultural University of Athens to optimise nutrient management in soilless culture. NUTRISENSE is on-line available via the link https://nutrisense.online/, and can be used to calculate optimal NS compositions for open and closed-loop soilless crops and readjust their composition whenever a new chemical analysis of the DS is available. NUTRISENSE was presented at the II International Symposium on Growing Media, Soilless Cultivation, and Compost Utilization in Horticulture in Ghent, Belgium in 2021 (Savvas et al., 2021), and some of its algorithms have been also reported by Neocleous and Savvas, 2022, and Savvas et al., 2023.

The standard commercial practice in soilless greenhouses is to send out to a laboratory a DS sample for chemical analysis, optimally every 7-15 days, but sometimes every 30 days or even less frequently. Based on the obtained results, the composition of the SS in open systems, or of the AS in CLS, is readjusted. However, the results from a laboratory analysis are mostly received several days after collection of the DS sample. Therefore, fast and frequent measurement of individual nutrient concentrations in the DS would improve the nutrient management efficiency in CLS. ISEs can estimate the concentration of a single ion in a multi-ion solution, such as a DS, because they have an ion-selective membrane that responds selectively to one analyte in the presence of other ions in a solution (Kim et al., 2013). Moreover, ISEs have practical advantages such as simple use, wide measurement range, rapid and direct measurement, without any need for addition of reagents for colour development as is the case with colorimetric and refractometric approaches (Cho et al., 2019; Peña-Fleitas et al., 2022). In this regard, they are attractive tools for daily estimation of DS composition in combination with an EC and a pH meter. In the last years, there are several publications presenting ISE systems, portable, manual, or automated, for application in soilless culture, which claim acceptable accuracy (Kim et al., 2017; Cho et al., 2019; Chowdhury et al., 2020; Han et al., 2020; Peña-Fleitas et al., 2021). Nevertheless, the use of ISEs is still at an experimental level and has not been adopted by commercial greenhouses yet. An important factor that can contribute to maximizing the anticipated benefits from the use of ISEs in CLS is the processing of the on-line obtained data by a suitable software. Such a software should take into consideration not only the engineering background of the ISEs and mathematical models but also the complex chemistry of the nutrient solutions and its interconnections with the nutrient requirements of plants grown in SCS. NUTRISENSE, as a software developed to optimize nutrition and fertilization of plants grown in SCS, includes a special application based on suitable algorithms to support the use of ISEs in CLS. The current paper reports some key algorithms deployed by NUTRISENSE to automatically calculate the nutrient injection rates needed to maintain a constant macronutrient composition in the SS when the actual composition of the DS is determined in real time using ISEs. Furthermore, the current study includes a simulated case study to illustrate the nutrient concentration changes occurring in the DS and the SS when the actual UCs in a particular crop deviate from those suggested in credible literature sources (e.g., Soneveld and Voogt, 2009), which are used as standard values in NUTRISENSE.

2 Materials and methods

2.1 System background

According to a first approach, to optimize the nutrient supply to a crop, the concentration (C_i) of the i nutrient (i = K, Ca, Mg, NH_4-N, NO_3-N, SO_4-S, P, Fe, Mn, Zn, Cu, B, Mo, Cl) in the SS must be equal to a target concentration that has been determined experimentally and validated in commercial application (C_{st}). Optimal nutrient concentrations for several plants grown in SCS have been proposed in various publications (de Kreij et al., 1999, Voogt and Sonneveld 2009, Savvas et al., 2013, etc.). However, in CLS the SS is a mix of the AS and the DS, while the composition of the DS is variable. To maintain constant nutrient levels in the SS despite the variability in the composition of the DS, the composition of the AS should be accordingly modified whenever new SS is prepared. However, this is possible only if the variations in the composition of the DS are monitored, which entails the use of ISEs.

Although this first approach is correct, the optimal nutrient concentrations in the SS do not always match the plant requirements, because the nutrient uptake rates by plants may also show some variability over time. To address this problem, the new algorithms included in NUTRISENSE specifically for the application of ISEs in CLS are working in combination with the algorithm proposed by Savvas et al. (2023) to readjust the nutrient concentrations in the added solution whenever the current concentration of the DS is determined. The algorithm presented by Savvas et al. (2023) calculates the actual UCs of plants cultivated in CLS for an interval between two successive DS sampling dates, e.g., every 14 days which is the common practice in modern greenhouses. Then, NUTRISENSE calculates new target concentrations for each individual nutrient in the AS aiming to maintain the nutrient levels in the root zone close to the optimum values for the specific plant species (de Kreij et al., 1999; Sonneveld and Voogt, 2009). There are two alternative methods for the preparation of the SS in CLS. The first alternate is the mixing of the DS with irrigation water up to the EC target for the mixture (E_m). Subsequently, a fertigation head adds stock solutions of fertilisers at rates aiming to achieve a nutrient input equal to the composition of the AS, up to the EC target for the SS (E_s). The second alternate is the preparation of the AS by the fertigation head with an EC target for the AS (E_a). Then, the AS is mixed with the DS up to the EC target for the SS (E_t). If the AS is modified frequently, a fertigation system with multiple stock solution tanks and a single fertiliser in each stock solution should be used (Savvas and Gruda, 2018; Blok et al., 2022). When such a fertigation system is used, NUTRISENSE calculates the injection rate of each single-fertiliser stock solution and not the masses of fertilisers needed to prepare new stock solutions as is the case in A/B stock solution systems (van Os et al., 2019; Savvas et al. 2023).

2.2 Determination of the macro-ion concentrations in the DS using ISEs

The data from the measurements of the ISEs are used by NUTRISENSE to estimate the current composition of the DS. This study will focus on the management of macro-nutrient because there are no reliable ISEs for micronutrients. ISEs for measuring K^+, Ca^{2+}, Mg^{2+}, NH_4^+, Na^+, NO_3^-, P, and Cl^- are available, and many studies reported their use with acceptable accuracy for the estimation of NS compositions (Kim et al., 2017; Cho et al., 2019; Chowdhury et al., 2020; Han et al., 2020; Peña-Fleitas et al., 2021). The anion-cation balance and empirical equations that link EC with the sum of the electrical charges can be used additionally to the data from ISE for the estimation of the DS. Savvas and Adamidis, (1999, 2000), proposed an empirical equation that link the EC of a NS with ΣC_i^+ or ΣC_i^-:

$$E = \frac{\Sigma C_i^+ + 1.462}{9.819} \quad (1)$$

where the E is the EC in dS m^{-1} and ΣC_i^+ in meq L^{-1}.

In DS, the equivalent sums of cation and anion concentrations (ΣC_i^+ and ΣC_i^- in meq L^{-1} , respectively) are estimated as functions of the molar concentrations (mmol L^{-1}) of each macroion.

$$\Sigma C_i^+ = [K^+] + 2 \cdot [Ca^{2+}] + 2 \cdot [Mg^{2+}] + [Na^+] + [NH_4{}^+] \quad (2)$$

$$\Sigma C_i^- = [NO_3{}^-] + [H_2PO_4{}^-] + 2 \cdot [SO_4{}^{2-}] + [Cl^-] + [HCO_3{}^-] \quad (3)$$

Furthermore, due to the cation-anion balance:

$$\Sigma C_i^+ = \Sigma C_i^- \quad (4)$$

Micronutrient cations and anions are neglected in (3) and (4), as their concentrations are much lower than those of macronutrients and, therefore, they do not have any impact in the anion to cation balance.

Currently, ISEs are available for the determination of all macro-cations and three of the macro-anions, particularly NO_3^-, P and Cl. When it is not possible to determine all the macronutrients, because an ISE is not available or the user has less than these eight ISEs in operation, NUTRISENSE estimates the undetermined nutrients based on the anion to cation balance. Using (1), (2), (3) and (4) in combination, it is possible to calculate the concentration of one cation, or anion, if the EC and the concentrations of the other four cations or anions are determined. If needed for the estimation of cations, it should be considered that Na^+ also can be estimated through models for some crops (Savvas et al., 2005, 2007, 2008; Trajkova et al., 2006; Varlagas et al., 2010; Neocleous and Savvas, 2016, 2017; Voogt and Bar-Yosef, 2019). In addition, NH_4-N levels in DS are very low, approximately 0-0.2 mM, if the pH is inside the acceptable range for the DS (5.5-6.5), because of nitrification and its preferential uptake over NO_3-N (Sonneveld and Voogt, 2009). Furthermore, NH_4-N is added to the NSs for pH management in the root zone, thus the Cs of NH_4-N is not readjusted by its level in the DS but based on pH value (Savvas et al., 2023). Hence, the concentration of NH_4-N can be ignored for the estimation of a nutrient based on the anion to cation balance. Similarly, for the estimation of anions, it should be considered that Cl^- also can be estimated through the same models used for the estimation of Na^+ in the DS. Furthermore, the HCO_3^- levels are very low (0.1-1.0 mmol L^{-1}) in the DS if the pH is inside the acceptable range for the DS (5.5-6.5). The sulfate concentration in the DS is calculated using (3) after solving for SO_4^{2-}.

2.3 Readjusting the composition of the supply solution (SS)

NUTRISENSE includes a database with target nutrient concentrations in the SS (C_{st}) for a wide range of greenhouse-grown crops based on several literature sources (de Kreij et al, 1999; Sonneveld and Voogt, 2009; Savvas et al., 2013). Thus, when the cultivated plant species is selected by the user of NUTRISENSE, the target nutrient concentrations in the SS are fixed and used as known parameters in the algorithms described below. When SS has to be prepared and supplied to a crop grown in a CLS, the macro-ion concentrations in the DS are determined using an ISE system and the data are transferred in real time to NUTRISENSE. At the same time, EC and pH sensors also transmit to NUTRISENSE the current EC and pH values in the DS.

According to the standard practice applied in CLS, the DS is initially mixed with irrigation water at a ratio adjusted automatically to obtain a preset EC (E_m) in the outgoing mix. Thus, NUTRISENSE first calculates the concentrations of all macro-ions in the mixture of DS and water using the following equation:

$$C_m = aC_d + (1 - a)C_w \tag{5}$$

where a is the target drainage fraction (0.0-1.0), and C_d and C_w are the concentrations of this nutrient in the DS and the raw water used to prepare NS, respectively. Subsequently, NUTRISENSE calculates the sum of the equivalent macro-cation concentrations (ΣC_i^+) using (2). The next step is the calculation of a target EC for the mix of DS and water (E_m) using (1). The estimated E_m is transmitted by NUTRISENSE to the system controlling the mixing ratio between DS and water. Thus, the nutrient concentrations in the mix will be those estimated using (5) when its EC is adjusted to E_m.

The injection rate of each nutrient (C_{nt}) to the mix of DS and water that is needed to achieve the target concentration of this nutrient in the SS (C_{st}) is calculated using the following equation:

$$C_{nt} = C_{st} - C_m \tag{6}$$

Consequently, by substituting (5) for C_{im} in (6) the following equation is obtained:

$$C_{nt} = C_{st} - aC_d - (1 - a)C_w \tag{7}$$

The C_{nt} values estimated using (7) are transmitted to a series of algorithms described by Savvas and Adamidis (1999, 2000), which are part of NUTRISENSE, to estimate the injection rate of each individual fertiliser. The estimated injection rates are transmitted from NUTRISENSE to a fertigation system working with single-fertiliser stock solutions and applied automatically in real time to the mix of DS and raw water.

In the above algorithm, only Equation (1) is empirical but its accuracy for NSs used in soilless culture has been proven in commercial practice. All other equations (2-7) are based on mass balance, while including either known or measured parameters and, thus, the accuracy of the estimated injection rates is high.

2.4 Readjusting the target nutrient concentrations in the SS

Although the accuracy in achieving the target concentrations in the SS (C_{st}) is high when working with ISE, this is not sufficient to ensure an optimal nutrient supply to the crop in the long term. As outlined in detail by Blok et al (2022) and Savvas et al. (2023), the composition of the NS supplied to a soilless cultivation has to be frequently readjusted following a chemical analysis of the DS. This is necessary because the standard recommended concentrations for every crop are average values determined experimentally and do not apply exactly in each individual crop. If no ISE are available, the standard practice in CLS is to readjust the composition of the AS aiming to harmonise nutrient supply with nutrient uptake. The composition of the SS is subsequently derived from mass balance models as the mix of the AS and the DS estimated at fortnightly intervals. However, when ISE are used, the current composition of the DS is known as it is constantly monitored, while the target composition of the AS is estimated by applying a modified algorithm presented below.

NUTRISENSE uses an algorithm suggested by Savvas et al. (2023) to calculate a readjusted concentration in the added solution (C_{ar}) for a particular period (i.e., fortnightly) that matches the current nutrient uptake rates during that period. Subsequently, C_{ua} is substituted in the following equation to obtain a readjusted target concentration for the SS (C_{sr}):

$$C_{sr} = aC_d + (1 - a)C_{ar} \tag{8}$$

where a is the target drainage fraction that is recycled, and C_d is the concentration of the particular nutrient in the drainage solution. Thus, during the next fortnight interval, the C_{st} in (6) will be replaced by C_{sr}.

2.5 Simulation study

To test the value of daily readjusting of AS using ISEs, a pilot study was conducted. The specific aims of this study were to test a) the range of deviation in DS composition caused by a range of ±10% deviations in the UC of the plants, and b) and the errors in the composition of SS that these deviations cause, for the macronutrients: K^+, Ca^{2+}, NO_3^--N and P. In the pilot study checked for cucumber the deviation after an interval of 14 days, which is the common between two subsequence readjustments of NS formula in modern greenhouses, where cucumber cultivated in CLS. It used the standard Dutch recommendations for target nutrient concentrations in root zone and mean uptake concentrations for K^+, Ca^{2+}, NO_3^-−N and P for cucumber, which are represented in Table 1 (de Kreij et al., 1999). Deviations in a range ±10% from the Dutch recommendations for the uptake concentrations reported to previous studies (Savvas et al., 2014, 2017; Ropokis et al., 2019), due to different climate condition, cultivar or rootstock, fruit load and greenhouse type. Table 2 shows the standard values for the daily volume of AS supplied to the crop (V_a), the time of applying the current NS formula (T_p), the volume sum of root solution and drainage solution (V_d) and the recycled drainage fraction (a) for a cucumber crop that are used to the pilot study, which are the standard values for a soilless cucumber cultivation.

3 Results and Discussion

Fig.1 shows the deviations of C_d imposed by deviations of ±10% in the C_u. Cucumber has standard potassium C_u, 6.5 mM and the target value for the root zone is 8 mM. If mean C_u deviated from 5.85 to 7.15 mM (±10%) for an interval of 14 days, the C_d will range from 3.45 to 12.55 mM (±57%) after these days. For calcium the standard C_u is 2.75 mM and the target value for the root zone is 6.5 mM. Deviations of mean C_u in the range of 2.48−3.03 mM (±10%) for 14 days have as a result ranged from 4.58 to 8.43 mM (±30%) to the value of C_d. Respectively, for nitrates and phosphorus the standard C_u are 11.75 and 1.25 mM and the target values for C_d are 18 and 0.9 mM. The ±10% deviations of mean C_u, 10.58−12.93 mM for nitrates and 1.13-1.38 mM for phosphorus, cause ±46% (9.78−26.23 mM) and ±97% (0.03−1.78 mM) to the C_d, respectively. These results show that common and reported in previous studies deviations from the literature suggested C_u, cause very extensive variations in DS composition. C_u deviations even smaller from ±10% range cause significant changes in C_d. For instance, a 4% deviation in C_u of potassium cause a 23% deviation of C_d, and a 6% deviation in C_u of calcium causes a 18% deviation of C_d from the target value in a cucumber crop. Respectively, a 4% deviation in nitrate C_u causes a 18% deviation of C_d target value and only a 2% deviation of phosphorus C_u causes a 19% deviation from the target C_d. Consequently, the DS composition significantly changes during the cultivation period as the C_u has small deviations from the literature and it is also mentioned by Sonneveld and Voogt, (2009). Low nutrient levels in the root environment can cause nutrient deficiency and respectively high nutrient levels cause osmotic stress, due to increasing EC, or even toxicity. The deviations from the target values for DS cause also nutrient imbalances in the root solution, such as in the K, Ca, Mg ratio, which are effective for plant nutrition (Neocleous and Savvas, 2015). A lower or a higher concentration of one nutrient in the root solution not only does affect the availability of this nutrient but also can affect the UC of other nutrients. The Ca^{2+} uptake is strongly reduced at low P and Cl concentrations. Increased K or NO_3^-−N uptake concentrations will reduce the uptake or the transport of Ca (Voogt and Sonneveld, 2004; Sonneveld and Voogt, 2009).

In CLS the deviation of the DS affects the accuracy of the SS composition. In Fig. 2 are shown the deviation of C_s from the target value, which is calculated for a specific DS composition, for K^+, Ca^{2+}, NO_3^-−N and P when C_d is in the range caused by the deviations of C_u from −10% to +10% of the target value. If potassium ranged ±57% (3.45−12.55 mM) from the target value in the DS, the error in the C_s is a range of ±20% (5.58−8.32 mM) from the target value (6.95 mM). The ±30% range, from 4.58 to 8.43 mM of calcium concentration in the DS, causes a ±15% range of error from the target value for C_s (3.88 mM) that is from 3.30 to 4.45 mM. Ranging from 9.78 to 26.23 mM (±46%) of the nitrates target value in DS (18 mM) causes deviation in the C_s from 11.18 to 16.09 mM (±18%). Finally, if phosphorus ranged ±97% (0.03−1.78 mM) from the target value in the DS, the C_s is ranging ±23% (0.88−1.41 mM) from the target value (1.15 mM). These deviations of the SS from its accurately calculated composition cause more wide deviations from the nutrients targets for DS composition and exacerbate rather than correct the nutrient imbalances in the root environment.

4 Conclusion

These results are highlighting the effect of the deviations in UC of the plants on DS composition. This problem can be overcome by a periodical recalculation of the actual UC through NUTRISENSE, based on a chemical analysis of DS, and the readjustment of the SS. In the interval between two chemical analyses of DS also may be some deviations of DS composition that affect the accuracy of SS preparation. ISEs systems can be used for a daily measuring of the macronutrient concentrations in DS. The new version of NUTRISENSE uses the data from the ISEs to estimate the DS composition daily and to readjust the AS composition to achieve accurate preparation of SS. The accuracy and reliability of each ISE system is the main issue that should be experimentally tested before the commercial demonstration of the system.cooperation and contribution. We are looking forward to seeing you at the Conference.

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References:

[1]. Blok, C., Barbagli, T., Voogt, W., Savvas, D., 2022. Overview of Developments in Recirculation of Drainage Solution for Crops on Growing Media. 31st IHC, 14-20 August 2022, Angers, Fr. Acta Hort (in press)

[2]. Cho, W.-J., Kim, H.-J., Jung, D.-H., Han, H.-J., Cho, Y.-Y., 2019. Hybrid Signal-Processing Method Based on Neural Network for Prediction of NO3, K, Ca, and Mg Ions in Hydroponic Solutions Using an Array of Ion-Selective Electrodes. Sensors 19, 1–17. https://doi.org/10.3390/s19245508

[3]. Chowdhury, M., Jang, B.E., Kabir, M.S.N., Lee, D.H., Kim, H.T., Park, T.S., Chung, S.O., 2020. Performance evaluation of commercial ion-selective electrodes for hydroponic cultivation system. Acta Hortic. 1296, 831–838. https://doi.org/10.17660/ActaHortic.2020.1296.105

[4]. De Kreij, C., Voogt, W., van den Bos, A.L., Baas, R., 1999. Bemestingsadviesbasis substraten. Proefstation voor Bloemisterij en Glasgroente. Vestiging Naaldwijk, The Netherlands.

[5]. Gallardo, M., Cuartero, J., Andújar de la Torre, L., Padilla, F.M., Segura, M.L., Thompson, R.B., 2021. Modelling nitrogen, phosphorus, potassium, calcium and magnesium uptake, and uptake concentration, of greenhouse tomato with the VegSyst model. Sci. Hortic. (Amsterdam). 279, 109862. https://doi.org/10.1016/j.scienta.2020.109862

[6]. Han, H.-J., Kim, H.-J., Jung, D.-H., Cho, W.-J., Cho, Y.-Y., Lee, G.-I., 2020. Real-time Nutrient Monitoring of Hydroponic Solutions Using an Ion-selective Electrode-based Embedded System. Prot. Hortic. Plant Fact. 29, 141–152. https://doi.org/10.12791/ksbec.2020.29.2.141

[7]. Kim, H.J., Kim, D.W., Kim, W.K., Cho, W.J., Kang, C.I., 2017. PVC membrane-based portable ion analyzer for hydroponic and water monitoring. Comput. Electron. Agric. 140, 374–385. https://doi.org/10.1016/j.compag.2017.06.015

[8]. Kim, H.J., Kim, W.K., Roh, M.Y., Kang, C.I., Park, J.M., Sudduth, K.A., 2013. Automated sensing of hydroponic macronutrients using a computer-controlled system with an array of ion-selective electrodes. Comput. Electron. Agric. 93, 46–54. https://doi.org/10.1016/j.compag.2013.01.011

[9]. Massa, D., Magán, J.J., Montesano, F.F., Tzortzakis, N., 2020. Minimizing water and nutrient losses from soilless cropping in southern Europe. Agric. Water Manag. 241, 106395. https://doi.org/10.1016/j.agwat.2020.106395

[10]. Neocleous, D., Savvas, D., 2022. Validating a smart nutrient solution replenishment strategy to save water and nutrients in hydroponic crops. Front. Environ. Sci. 10, 1–12. https://doi.org/10.3389/fenvs.2022.965964

[11]. Neocleous, D., Savvas, D., 2017. Simulating NaCl accumulation in a closed hydroponic crop of zucchini: Impact on macronutrient uptake, growth, yield, and photosynthesis. Zeitschrift fur Pflanzenernahrung und Bodenkd. 180, 283–293. https://doi.org/10.1002/jpln.201600338

[12]. Neocleous, D., Savvas, D., 2016. NaCl accumulation and macronutrient uptake by a melon crop in a closed hydroponic system in relation to water uptake. Agric. Water Manag. 165, 22–32. https://doi.org/10.1016/j.agwat.2015.11.013

[13]. Neocleous, D., Savvas, D., 2015. Effect of different macronutrient cation ratios on macronutrient and water uptake by melon (Cucumis melo) grown in recirculating nutrient solution. J. Plant Nutr. Soil Sci. 178, 320–332. https://doi.org/10.1002/jpln.201400288

[14]. Neocleous, D., Savvas, D., 2013. Response of hydroponically-grown strawberry (Fragaria ? ananassa Duch.) plants to different ratios of

K:Ca:Mg in the nutrient solution By 88, 293–300.

[15]. Peña-Fleitas, M.T., Gallardo, M., Padilla, F.M., Rodríguez, A., Thompson, R.B., 2021. Use of a portable rapid analysis system to measure nitrate concentration of nutrient and soil solution, and plant sap in greenhouse vegetable production. Agronomy 11. https://doi.org/10.3390/agronomy11050819

[16]. Peña-Fleitas, M.T., Grasso, R., Gallardo, M., Padilla, F.M., de Souza, R., Rodríguez, A., Thompson, R.B., 2022. Sample temperature affects measurement of nitrate with a rapid analysis ion selective electrode system used for N management of vegetable crops. Agronomy 12. https://doi.org/10.3390/agronomy12123031

[17]. Ropokis, A., Ntatsi, G., Kittas, C., Katsoulas, N., Savvas, D., 2019. Effects of temperature and grafting on yield, nutrient uptake, and water use efficiency of a hydroponic sweet pepper crop. Agronomy 9, 1–15. https://doi.org/10.3390/agronomy9020110

[18]. Savvas, D., Adamidis, K., 1999. Automated management of nutrient solutions based on target electrical conductivity, pH, and nutrient concentration ratios. J. Plant Nutr. 22, 1415–1432. https://doi.org/10.1080/01904169909365723

[19]. Savvas, D., Adamidis, K., 2000. Erratum. J. Plant Nutr. 23, 1371–1371. https://doi.org/10.1080/01904160009382106

[20]. Savvas, D., Gruda, N., 2018. Application of soilless culture technologies in the modern greenhouse industry - A review. Eur. J. Hortic. Sci. 83, 280–293. https://doi.org/10.17660/eJHS.2018/83.5.2

[21]. Savvas, D., Ntatsi, G., Rodopoulou, M., Goumenaki, F., 2014. Nutrient uptake concentrations in a cucumber crop grown in a closed hydroponic system under mediterranean climatic conditions as influenced by irrigation schedule. Acta Hortic. 1034, 545–552. https://doi.org/10.17660/ActaHortic.2014.1034.69

[22]. Savvas, D., Gianquinto, G.P., Tüzel, Y., Gruda, N., 2013. Soilless Culture. In: Good Agricultural Practices for Greenhouse Vegetable Crops. Principles for Mediterranean Climate Areas. Food and Agriculture Organization of the United Nations, Plant Production and Protection Paper 217, Rome, pp. 303-354, (http://www.fao.org/3/a-i3284e.pdf).

[23]. Savvas, D., Drakatos, S., Panagiotakis, I., Ntatsi, G., 2021. NUTRISENSE: a novel software to automatically control nutrient supply in closed hydroponic crops based either on off-line chemical analyses or on ion-selective electrodes. Acta Hortic. 1317, 215–221. https://doi.org/10.17660/ActaHortic.2021.1317.24

[24]. Savvas, D., Chatzieustratiou, E., Pervolaraki, G., Gizas, G., Sigrimis, N., 2008. Modelling Na and Cl concentrations in the recycling nutrient solution of a closed-cycle pepper cultivation. Biosyst. Eng. 99, 282–291. https://doi.org/10.1016/j.biosystemseng.2007.10.008

[25]. Savvas, D., Meletiou, G., Margariti, S., Tsirogiannis, I., Kotsiras, A., 2005. Modeling the relationship between water uptake by cucumber and NaCl accumulation in a closed hydroponic system. HortScience 40, 802–807. https://doi.org/10.21273/hortsci.40.3.802

[26]. Savvas, D., Mantzos, N., Barouchas, P.E., Tsirogiannis, I.L., Olympios, C., Passam, H.C., 2007. Modelling salt accumulation by a bean crop grown in a closed hydroponic system in relation to water uptake. Sci. Hortic. (Amsterdam). 111, 311–318. https://doi.org/10.1016/j.scienta.2006.10.033

[27]. Savvas, D., Öztekin, G.B., Tepecik, M., Ropokis, A., Tüzel, Y., Ntatsi, G., Schwarz, D., 2017. Impact of grafting and rootstock on nutrient-to- water uptake ratios during the first month after planting of hydroponically grown tomato. J. Hortic. Sci. Biotechnol. 00, 1–9. https://doi.org/10.1080/14620316.2016.1265903

[28]. Savvas, D., Giannothanasis, E., Ntanasi, T., Karavidas, I., Drakatos, S., Panagiotakis, I., Neocleous, D., Ntatsi, G., 2023. Development and validation of a decision support system to maintain optimal nutrient levels in crops grown in closed-loop soilless systems. Agric. Water Manage. (under publication).

[29]. Sonneveld, C., Voogt, W., 2009. Plant nutritions of greenhouse crop, Plant nutritions of greenhouse crop. Springer Dordrecht Heidelberg London New York.

[30]. Thompson, R.B., Gallardo, M., Rodríguez, J.S., Sánchez, J.A., Magán, J.J., 2013. Effect of N uptake concentration on nitrate leaching from tomato grown in free-draining soilless culture under Mediterranean conditions. Sci. Hortic. (Amsterdam). 150, 387–398. https://doi.org/10.1016/j.scienta.2012.11.018

[31]. Trajkova, F., Papadantonakis, N., Savvas, D., 2006. Comparative effects of NaCl and CaCl2 salinity on cucumber grown in a closed hydroponic system. HortScience 41, 437–441. https://doi.org/10.21273/hortsci.41.2.437

[32]. Tzerakis, C., Savvas, D., Sigrimis, N., Mavrogiannopoulos, G., 2013. Uptake of Mn and Zn by cucumber grown in closed hydroponic systems as influenced by the Mn and Zn concentrations in the supplied nutrient solution. HortScience 48, 373–379. https://doi.org/10.21273/hortsci.48.3.373

[33]. Varlagas, H., Savvas, D., Mouzakis, G., Liotsos, C., Karapanos, I., Sigrimis, N., 2010. Modelling uptake of Na+ and Cl- by tomato in closed-cycle cultivation systems as influenced by irrigation water salinity. Agric. Water Manag. 97, 1242–1250. https://doi.org/10.1016/j.agwat.2010.03.004

[34]. Van Os, E.A., Gieling, T.H., Heinrich Lieth, J., 2019. Technical equipment in soilless production systems, in: Soilless Culture: Theory and Practice. Elsevier B.V., pp. 587–635. https://doi.org/10.1016/B978-0-444-63696-6.00013-X.

[35]. Voogt, W., Bar-Yosef, B., 2019. Water and nutrient management and crops response to nutrient solution recycling in soilless growing systems in greenhouses, in: Soilless Culture: Theory and Practice Theory and Practice. Elsevier B.V., pp. 425–507. https://doi.org/10.1016/B978-0-444-63696-6.00010-4

[36]. Voogt, W., Sonneveld, C., 2004. Interations between nitrate (NO_3) and chloride (Cl) in nutrient solutions for substrate grown tomato. Acta Hortic. 644, 359–368. https://doi.org/10.17660/ActaHortic.2004.644.48

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Tables

Table 1. Standard recommendations for target nutrient concentrations in the root zone and mean uptake concentrations for cucumber used in the current simulation study (de Kreij 1999).

Nutrient	Uptake concentration	Target concentration for the DS	units
K^+	6.5	8	mM
Ca^{2+}	2.75	6.5	mM
$NO3^-$-N	11.75	18	mM
P	1.25	0.9	mM

Table 2. Values introduced to NUTRISENSE to perform the simulation study.

Parameter		units
Daily volume of added solution supplied to the crop (V_a)	2	L plant^{-1} d^{-1}
Volume sum of root solution and drainage solution (V_d)	4	L plant^{-1}
Time applying the current NS formula (T_p)	14	days
Recycled drainage fraction (a)	0.30	

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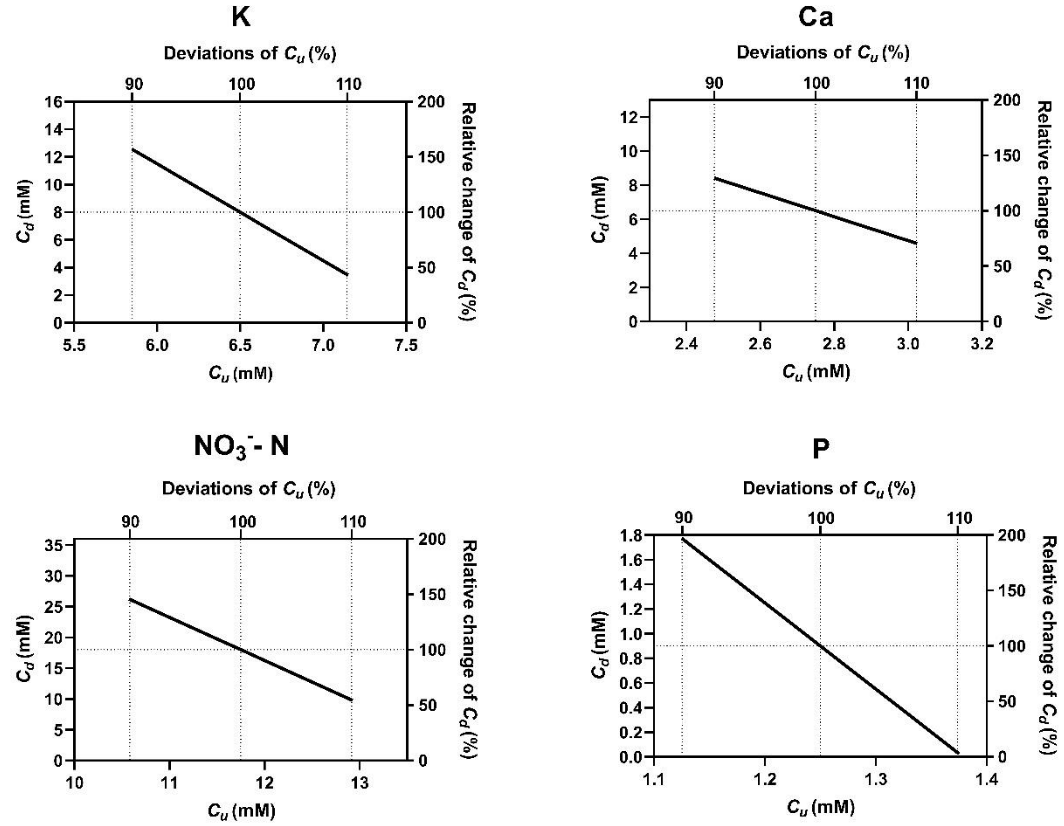

Figures

Figure 1: Concentrations of potassium, calcium, nitrates, and phosphorus in the drainage-root solution (C_d) as functions of ±10% deviations from the standard value in the mean uptake concentration (C_u) of cucumber for a period of 14 days. The horizontal dotted lines denote the target value for the drainage-root solution (C_d). The vertical dotted lines denote the standard and the ±10% values of the uptake concentrations (C_u).

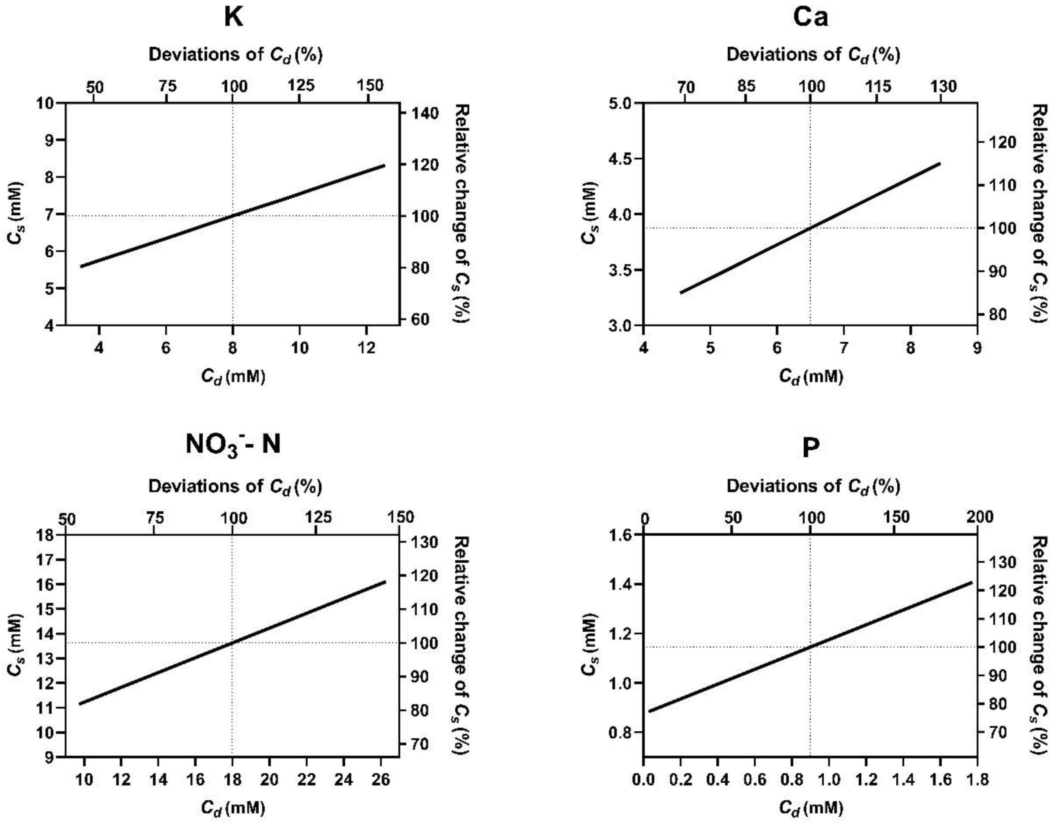

Figure 2: Concentrations of potassium, calcium, nitrates, and phosphorus in the supply solution (C_s) as functions of deviations in the drainage solution (C_d) caused by ±10% variations from the standard value in the mean uptake concentration (C_u) of cucumber for a period of 14 days. The horizontal dotted lines denote the target value for the supply solution (C_s). The vertical dotted lines denote the target value for the drainage-root solution (C_d).

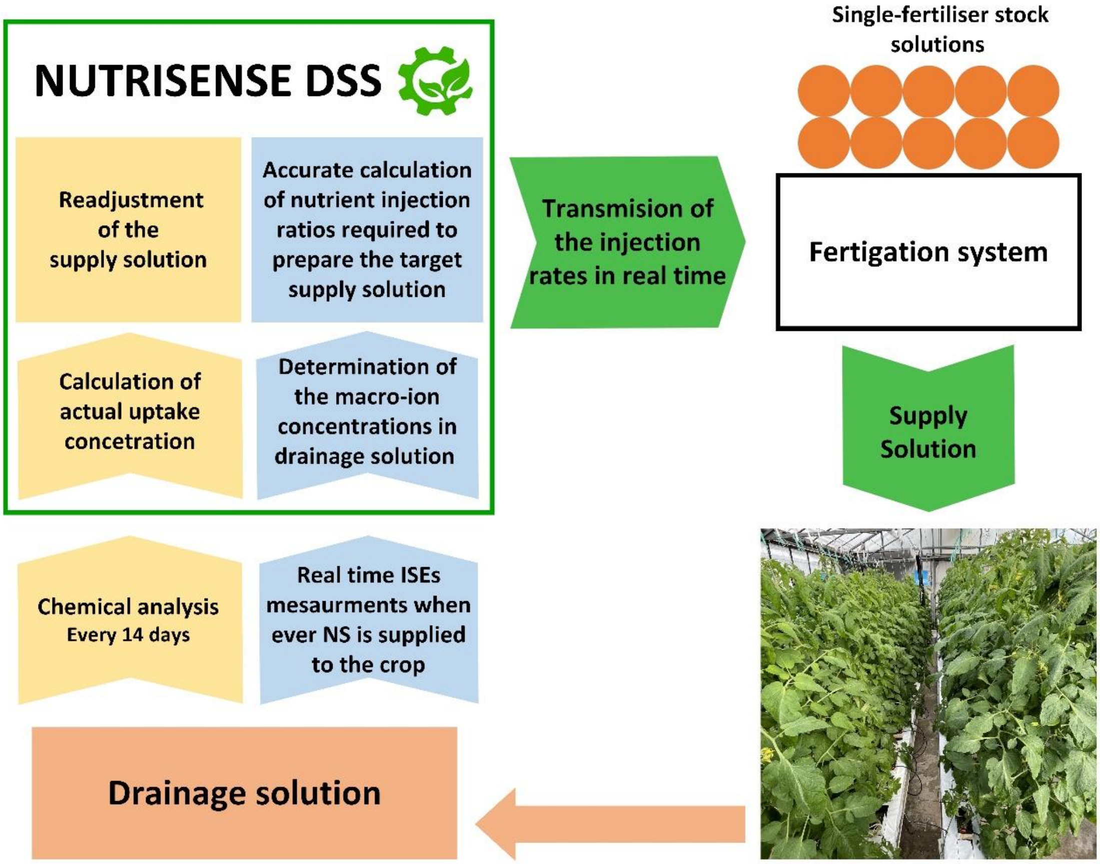

Figure 3: Schematic outline of the algorithm applied via the DSS NUTRISENSE to optimise nutrient supply in closed-loop soilless cultivations using ion selective electrodes.