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Review

State of the Art and New Technologies to Recycle the Fertigation Effluents in Closed Soilless Cropping Systems Aiming to Maximise Water and Nutrient Use Efficiency in Greenhouse Crops

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Abstract: Inappropriate fertilisation results in the pollution of groundwater with nitrates and phosphates, eutrophication in surface water, emission of greenhouse gasses, and unwanted N deposition in natural environments, thereby harming the whole ecosystem. In greenhouses, the cultivation in closed-loop soilless culture systems (CLSs) allows for the collection and recycling of the drainage solution, thus minimising contamination of water resources by nutrient emissions originating from the fertigation effluents. Recycling of the DS represents an ecologically sound technology as it can reduce water consumption by 20–35% and fertiliser use by 40–50% in greenhouse crops, while minimising or even eliminating losses of nutrients, thereby preventing environmental pollution by NO_3^- and P. The nutrient supply in CLSs is largely based on the anticipated ratio between the mass of a nutrient absorbed by the crop and the volume of water, expressed as mmol L^{-1}, commonly referenced to as "uptake concentration" (UC). However, although the UCs exhibit stability over time under optimal climatic conditions, some deviations at different locations and different cropping stages can occur, leading to the accumulation or depletion of nutrients in the root zone. Although these may be small in the short term, they can reach harmful levels when summed up over longer periods, resulting in serious nutrient imbalances and crop damage. To prevent large nutrient imbalances in the root zone, the composition of the supplied nutrient solution must be frequently readjusted, taking into consideration the current nutrient status in the root zone of the crop. The standard practice to estimate the current nutrient status in the root zone is to regularly collect samples of drainage solution and determine the nutrient concentrations through chemical analyses. However, as results from a chemical laboratory are available several days after sample selection, there is currently intensive research activity aiming to develop ion-selective electrodes (ISEs) for online measurement of the DS composition in real-time. Furthermore, innovative decision support systems (DSSs) fed with the analytical results transmitted either offline or online can substantially contribute to timely and appropriate readjustments of the nutrient supply using as feedback information the current nutrient status in the root zone. The purpose of the present paper is to review the currently applied technologies for nutrient and water recycling in CLSs, as well as the new trends based on ISEs and novel DSSs. Furthermore, a specialised DSS named NUTRISENSE, which can contribute to more efficient management of nutrient supply and salt accumulation in closed-loop soilless cultivations, is presented.

Keywords: closed-loop soilless culture; drainage solution; water recycling; nutrient recirculation; decision support systems; NUTRISENSE

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1. Introduction

Inappropriate crop fertilisation not only reduces yield and produce quality but also leads to nutrient emissions into the air and water resources, among which nitrogen and phosphorus result in serious environmental impacts. These emissions have serious negative consequences for the environment, including groundwater pollution rendering water undrinkable, eutrophication of aquatic ecosystems, and greenhouse gas emissions. The emission of nitrogen in agricultural crops occurs either in gaseous form due to denitrification and ammonia volatilisation, or in mineral form through the fertigation effluents [1]. Over-fertilisation with manure and inorganic P fertilisers for many years has resulted in saturation of the retention capacity for P in many agricultural soils and, consequently, P loss by run-off and leaching to surface water resources results, together with nitrate emissions, in eutrophication of surface water [2]. In view of these serious threats to the ecosystem, the European Union has set a strategic target in the Green Deal to reduce fertiliser consumption by 20% and nutrient losses by 50% by 2030 [3]. To mitigate the pollution of water resources caused by inappropriate fertilisation and irrigation practices, there is an urgent need to apply new agricultural production approaches and innovative technologies for crop management aiming to reduce inputs and extend the circularity of nutrients.

Greenhouse cultivation is an intensive form of plant production and thus inappropriate fertilisation of greenhouse crops can result in considerable emissions of nutrients to the environment. Soilless culture systems (SCSs) constitute the dominant cultivation technique in the modern greenhouse industry. The soilless crops are distinguished into open or closed-loop systems depending on the management of the drained solution, which can be either discharged to the environment or collected and recycled. Open soilless culture systems are easier to manage as the composition of the supplied nutrient solution is completely controlled by the grower. However, open systems have been criticised as inefficient from an environmental point of view because they result in the waste of nutrients and water, and pollution of the water resources by the discharged leachate. To minimise the pollution of water by nutrient emissions originating from the fertigation of greenhouse crops and to render greenhouse production more sustainable and environment-friendly, closed-loop SCSs have been developed, henceforth abbreviated as CLSs. Nevertheless, crop nutrition is more complicated in CLSs than in open systems because the composition of the recycled DS is variable over time and unknown to the growers. Furthermore, in CLSs, the DS should be treated before its recycling to eliminate pathogens, thereby avoiding the spread of diseases from a small spot of infection to the whole crop. Despite these disadvantages, there is a shift from open soilless systems to CLSs due to their environmental benefits and the substantial reduction in fertilizer and water use without compromising yield performance. Therefore, the modern technologies applied in CLSs are outlined in more detail in the current paper.

2. Plant Nutrition in Soilless Cultivations

In soilless cultivations grown on inert substrates or in pure NS without any aggregate, the nutrition of the plants relies exclusively on fertigation, i.e., on the supply of NS to the crop via the irrigation system. The roots of the plants are in contact with the root solution and thus the satisfaction of their nutritional requirements depends directly on the nutrient levels in the root environment, irrespective of whether they grow in the soil or soilless systems. In soil-grown crops, the nutrient status in the root environment depends on the quantity of the nutrient reserves and the rate at which they are released to the soil solution. Hence, the nutrient status in the roots of soil-grown crops cannot be easily and quickly altered by crop fertilisation practices. However, the nutrient reserves in the root zone of soilless-grown crops are limited because the available substrate volume for root development is significantly less than in plants grown in soil. As a consequence, the nutrient status in the root environment of soilless crops may exhibit considerable fluctuations from day to day. Thus, the main objective of an efficient nutrient management system in soilless crops should be to maintain an optimal nutrient status in the root zone by properly modifying fertilisation practices whenever needed to achieve this goal.

Consequently, to ensure optimal nutrition in a soilless crop, the composition of the NS supplied to a crop should be considered a variable that may change frequently, aiming to achieve the primary objective, which is the maintenance of a target nutrient status in the root environment [4]. In other words, the nutrient status in the root zone is the strategic target, while the rates of external nutrient supply via fertigation represent the tactics, which may be altered during the cropping period to achieve the strategic target. Applying this concept in soilless culture means that for each crop a target nutrient composition has to be maintained in the root solution, using as a tool the composition of the NS supplied to the crop. This concept was introduced by Dutch scientists [5–7] and is referenced as the "Dutch nutrient recommendation system" [8].

The nutrients supplied via the NS to a soilless cropping system are removed from this system either via plant uptake or drainage solution [8]. If the removal of nutrients from the system via these two paths is lower or higher than the supply, the excessive or the missing nutrients will accumulate or deplete, respectively, in the root zone. Thus, to maintain optimal nutrient levels in the root zone of a soilless crop, which is the strategic target, the nutrient supply should be equal to the removal of nutrients via both paths, i.e., plant uptake and drainage. In CLSs, there is no output via drainage, while in open soilless cropping systems, the output of nutrients via the DS can be partly controlled by properly adjusting the drainage fraction. The only output of nutrients in CLSs is due to uptake by the crop, but this can be only roughly predicted if credible experimental data are available.

In Figure 1, the parameters involved in the supply of NS to soilless cultivations in both open and closed systems and the relevant terminologies are schematically outlined.

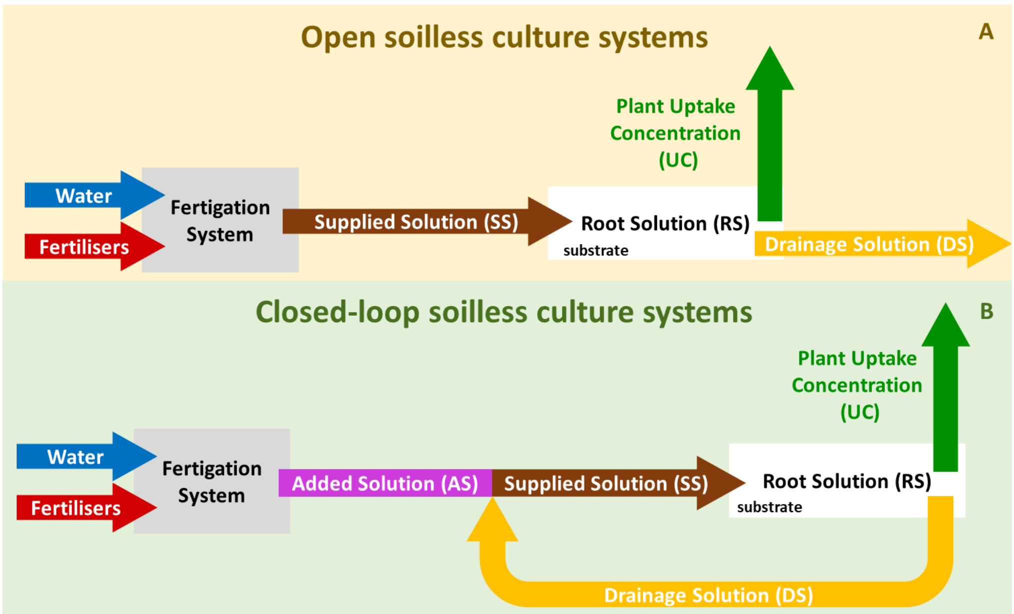

Figure 1. Schematic representation of the process of NS preparation in open (**A**) and closed-loop soilless cropping systems (**B**) and the terminologies used for the different parameters involved. Water: the raw water used for the preparation of NS; Fertilisers: liquid concentrated solutions (CSs) of water-soluble fertilisers used to add nutrients to the NS; Plant Uptake Concentrations (UCs): the ratios between each nutrient and the volume of water absorbed by the plant. Drainage solution (DS): the NS that drains out of the root zone after each irrigation event. Supplied solution (SS): the NS that is ultimately supplied to the crop, which in open SCSs is fresh NS prepared by mixing water with fertilisers, while in closed-loop SCSs it is the mixture of nutrients, water, and DS. Root solution (RS): the NS that is in immediate contact with the plant roots. Added solution (AS): an NS with concentrations corresponding to the ratios between the net nutrient input and the net water input (excluding the input of DS), when preparing SS in CLSs.

In both open and closed-loop SCSs, the NS that is ultimately supplied to the crop is termed supplied solution (SS). In substrate-grown crops, when the plants are irrigated through a drip irrigation system, the SS is frequently referenced as a "drip solution". In open SCSs (Figure 1A), the SS is simply prepared by injecting liquid stock solutions of fertilisers into irrigation water at rates resulting in a pre-set electrical conductivity (EC) in this, using suitable equipment termed "fertigation system" (FS). In CLSs (Figure 1B), the SS is prepared by mixing raw water, stock solutions of fertilisers, and DS at suitable rates. In CLSs, the masses of plant nutrients added through the fertilisers and the volume of raw water added to the DS to prepare SS correspond to specific nutrient-to-water rations, which are considered concentrations of a solution termed added solution (AS) [8]. The AS constitutes the net input of nutrients and water to the SS, while the DS provides nutrients and water to the SS that are already in the system.

The ratio between the mass of a plant nutrient and the volume of water removed from soilless cultivation through plant uptake, expressed as mmol L^{-1} (mM), corresponds to a concentration of this nutrient, which is termed "uptake concentration" (UC) in the international scientific literature [6,8,9]. The UCs of all plant nutrients correspond to a theoretical NS that fully covers the plant's needs but does not exist as a solution. In the international literature, there are experimental data for UCs of a wide range of plant species cultivated in SCSs [5,6,10–13].

The NS retained in the pores of the substrate, in troughs, or any other containers used for plant growth is termed "root solution" (RS), as it is in contact with the root system of the plants. When plants are grown out of the soil using a substrate as a rooting medium, part of the RS drains out of the root zone as DS and, consequently, the composition of the RS and the DS is almost identical. Therefore, in most cases, the management of nutrition in soilless crops is based on sampling and analysing DS and considering its composition as identical to that of the RS [14]. The indirect determination of the RS composition by measuring the composition of the DS is a common practice because the collection of RS samples directly from the substrates is difficult (except for rockwool), while the obtained samples are less representative of the whole crop than a sample of DS originating from a large crop area.

The mutual ratios between nutrients in the plant tissues are roughly similar in different crop species, although the differences are negligible. Based on this fact, a standard NS composition was developed by Hoagland and Arnon (1950) [15] and is used even today in plant nutrition studies. However, fine-tuning the composition of the NS supplied to crops to match the specific requirements of each cultivated species can substantially improve crop performance, especially in commercial greenhouses. The nutrients that should be essentially added to water to prepare NS include six macronutrients (K, Ca, Mg, N, P, S) and six micronutrients (Fe, Mn, Zn, Cu, B, Mo). Chloride is needed in very tiny amounts, which are always available in the NS, originating either from the mineral composition of the water or from fertiliser impurities. Furthermore, the nutrients should be supplied in specific forms that can be utilized by the plants. The essential nutrients contained in an NS and the forms in which they are supplied are shown in Table 1.

Table 1. Essential nutrients added to water to prepare nutrient solutions and the forms they are supplied in.

Macronutrient	Chemical Form	Micronutrient	Chemical Form
Nitrogen	NO_3^-, NH_4^+	Iron	Fe^{2+}
Phosphorus	$H_2PO_4^-$	Manganese	Mn^{2+}
Sulphur	SO_4^{2-}	Zink	Zn^{2+}
Potassium	K^+	Copper	Cu^{2+}
Calcium	Ca^{2+}	Boron	H_3BO_3
Magnesium	Mg^{2+}	Molybdenum	MoO_4^{2-}

Plants can selectively absorb most nutrients from the external solution to cover their specific nutritional requirements. Therefore, the nutrient concentrations in the root zone of plants grown in soilless cropping systems can fluctuate within a wide range. However, to maximize yield and quality in commercial soilless cultivations, it is important to provide the nutrients to the plants at rates that best meet their specific requirements. To achieve this objective, the composition of the supplied NS has to be precisely adapted to the special nutritional needs of each cultivated plant species. To address this need, NS formulae tailored to the special nutritional needs of each greenhouse crop species have been developed by several investigators (e.g., De Kreij et al. (1999); Sonneveld and Voogt (2009) [5,6]).

To specify an optimal concentration of a certain nutrient in the SS for a crop species, two parameters must be determined experimentally: the mean UC and the optimal concentration of this nutrient in the RS [4,8]. As suggested from previous experimental results, the UC depends on the concentrations of the respective nutrients in the root zone [12,16]. The impact of the RS composition on the UCs may arise from differences in nutrient uptake mechanisms. Calcium is absorbed passively from the apical parts of the root hairs via mass-flow mechanisms [17], while potassium is taken up selectively [18,19]. Furthermore, magnesium is selectively taken up, but the uptake mechanisms are not as efficient as those of potassium, and thus mechanisms based on mass-flow transport play an important role [20,21]. Since the uptake of Ca and Mg is mainly determined by mass flow rates rather than active uptake at the expense of metabolic energy, their concentrations in the root environment should be substantially higher than their UCs to ensure uptake rates that fully cover plant needs [22]. The same is also valid for sulphates. In contrast, for monovalent ions such as K^+ and $H_2PO_4^-$, optimal uptake rates by plants are achieved with substantially smaller differences between their concentrations in the root environment and their UCs [6].

In soilless culture, the total salt concentration in the root solution is considered one of the most important parameters determining yield and produce quality. The total salt concentration in the NS is expressed as electrical conductivity (EC, dS m^{-1}) because this quantity can be easily and accurately measured in the greenhouse using portable EC meters. Many studies have shown that the crop yield in a soilless cultivated crop decreases as the EC in the RS increases, and the yield decrease is linearly or curvilinearly associated with the increase in the EC in the SS above a threshold value [6,23]. Salinity problems in soilless cultures may occur either due to shortcomings in nutrient management resulting in an oversupply of some macronutrients, or due to high Na^+ concentrations in the raw water used to prepare NS [4].

The pH of the RS also affects yield and fruit quality as it has a strong impact on the availability of some nutrients to the crop. More specifically, too high pH levels in the RS, i.e., values higher than 6.3–6.5, depending on the crop species, restrict the availability of Fe, Mn, Cu, and Zn due to partial conversion of the active bivalent cations into $M(OH)_2$ (M = Fe, Mn, Zn, or Cu) which precipitate and are thus unavailable to plants. Nevertheless, due to the use of Fe chelates in NSs destined for soilless cultures, substantial amounts of Mn, Zn, and Cu are chelated as pH increases, and therefore their availability to plants with increasing pH of the RS is a more complex issue [6,24]. At pH levels below 5.0, there is a high risk of Mn and/or Al toxicity due to the partial conversion of their oxides into active Mn^{2+} and Al^{3+} ions. Furthermore, pH levels lower than 5 may cause direct H^+ injury in the root tissues [25]. P availability also depends on the pH of the RS. Thus, when the pH of the RS increases to levels higher than 7, most of the $H_2PO_4^-$, which is the form of P available to plants, is converted into HPO_4^{2-}, which is a form that is sparingly available to plants, while at pH levels lower than 5, substantial amounts of P remain in the undissociated form of H_3PO_4, which is unavailable to plants [26,27]. Furthermore, a combination of too-low pH and high NH_4-N concentrations in the RS restricts the uptake of Ca [6].

To maintain the pH of the RS within the desired range of 5.5–6.5, the pH of the SS solution is adjusted to 5.5 or 5.4 because the pH, after its adjustment to the target level, tends to increase. The following chemical equilibrium equation is involved in the adjustment of the pH to the target level in the SS [28]:

$$HCO_3^- + H_3O^+ \leftrightarrow H_2CO_3 + H_2O \quad K_{a1} = 10^{-6.3} \tag{1}$$

In (1), carbonic acid dissociates into H_2O and CO_2 but most of the CO_2 escapes progressively into the air, and thus the equilibrium in (1) moves to the right. Consequently, the concentration of H_3O^+ on the left of (1) decreases, and concomitantly, the pH values of the SS and the RS increase. To counteract the increase in pH due to the release of CO_2 from the SS and the RS, the SS should contain some nitrogen in the form of NH_4-N. Ammonium is preferentially absorbed by plants over nitrate, and this affects the balance between anion and cation uptake. To maintain the electrochemical equilibrium in the cells, the roots extrude protons, lowering the medium pH [29,30]. Furthermore, the nitrification of NH_4^+ in the RS also contributes to a decrease in the pH. Consequently, the manipulation of [NH_4-N]:[NO_3-N] in the SS without altering the total N concentration can be an efficient tool for maintaining the pH within the target range [22].

3. Crop Fertigation in Closed Soilless Systems

3.1. Feasibility of Closed Soilless Systems

In CLSs, the fertigation effluents, henceforth termed drainage solution (DS), are collected and recycled. The main environmental advantage of CLSs is the elimination of surface and underground water pollution, as nitrogen and phosphorus emissions originating from DS discharge are eliminated or at least drastically reduced. Moreover, the recycling of fertigation effluents reduces irrigation water and fertiliser consumption by more than 20–35% and 40–50%, respectively [4]. CLSs are mandatory in northern European countries, such as The Netherlands, to avoid contamination of water resources by nutrient emissions [14]. However, CLSs are not common in southern European countries and many other countries in the world. The main bottleneck in the adoption of DS recycling in soilless cultures is the presence of sodium at relatively high concentrations in the water used to prepare nutrient solution (NS), which leads to Na^+ accumulation in the recycled DS, and, concomitantly, in exposure of the crop to salinity stress [6,14,31]. Furthermore, the variable nutrient concentrations in the DS, in combination with shortcomings of the local advisory services, complicate the maintenance of optimal nutrient levels in the root environment of the crops [4].

3.2. Nutrient Solution Management in CLSs

Inappropriate composition of the SS can cause nutrient imbalances in the root environment, which may affect plant growth through nutrient deficiency, toxicity, or salinity stress [6,32–34]. Managing plant mineral nutrition by providing SS with optimal composition is a big challenge in CLSs, as the composition of the DS, which is a constituent of the SS, can vary with time due to temporal variations in nutrient uptake rates. Fluctuations in UCs have been observed not only between different plant species but also in the same species between different cultivars [10,35] or under different climatic conditions [36] or stress conditions, such as salinity stress due to Na^+ accumulation [35]. To address the challenges associated with maintaining optimal nutrient supply to crops in the CLSs despite the unpredictable variations in the composition of the DS, two alternative concepts can be deployed. The first concept is based on a target nutrient composition for the SS, while the second concept is based on a target nutrient composition of the AS [5,37]. Both concepts are based on regularly monitoring the mineral composition of the DS.

Based on the concept of a target concentration of the SS, the composition of the DS is used to estimate the composition of the mix of DS and water. Subsequently, the nutrient concentrations in the mix are deducted from the target nutrient concentrations in the SS to obtain the rates of nutrient injection through fertilisers. Based on the concept of a target concentration in the AS, an AS with concentrations equal to the anticipated UCs is supplied. Thus, the rates of nutrient input (concentrations in the AS) are set equal to those of nutrient output from the system (UCs). Indeed, the only net nutrient input in CLSs is the AS, and the only nutrient output is the plant uptake because no DS is discharged. If the concentration of a nutrient in the AS is higher or lower than its UC, accumulation or depletion, respectively, of this nutrient in the root zone would gradually occur.

The UC of a nutrient fluctuates within a relatively narrow range under controlled greenhouse conditions when the concentration of this nutrient is roughly stable in the root zone of the plants [38]. However, some variation in the UC of a nutrient may occur during the cropping period due to changes in (i) the level of this nutrient in the root zone, (ii) microclimatic parameters, (iii) fruit load, and (iv) any other factor that can alter the nutrient needs of the plants [16,36]. 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 are representative of the root solution composition [6], to adapt to current crop demands [4].

Water culture systems such as the nutrient film technique (NFT), the deep flow technique (DFT), the floating system, and aeroponics are essentially operated as CLSs [11]. These systems are mostly used for the production of leafy vegetables. In these cropping systems, the nitrate content in the edible plant parts is much more effectively controlled without compromising the yield by substantially reducing the nitrate concentration in the added solution for some days before harvesting. Thus, the safety of leafy vegetables produced as hydroponic crops is higher than that of leafy vegetables produced as soil-grown crops. The reduction in the nitrate supply for a few days before harvesting can be compensated for by an equivalent increase in the sulphate or chloride concentration in the added solution [11]. Finally, the microelement content of vegetables produced in CLSs is much better regulated than in soil-grown crops by properly changing their concentrations in the added solution, taking into consideration their levels in the drainage solution, which are frequently determined.

3.3. Sodium Accumulation in Closed-Loop Soilless Culture Systems

The high Na^+ concentration in the raw water used to prepare NS is the bottleneck in DS recycling. The UCs of Na^+ by most cultivated plants are generally much lower than the Na^+ concentrations in the water sources commonly used for irrigation [14,31,39–41]. Raw water with moderately high Na^+ concentration can be used in CLSs if mixed with appropriate amounts of rainwater. However, this option is not available for growers in regions with low yearly rainfall, like those in many parts of the Mediterranean basin, who face serious problems with excessively high Na^+ levels in the available water sources used for NS preparation [42]. The Na^+ concentration in the AS is identical to that in the water used to prepare it, as no Na^+ is added to NSs through fertilisers. Furthermore, the Na^+ UC is closely associated with the Na^+ concentration in the RS [31,40,41]. Therefore, Na^+ gradually accumulates in a CLS up to a level imposing a Na^+ UC equal to the Na^+ level in the AS.

If the concentration of an ion in the AS exceeds that in the UC, this ion gradually accumulates in the RS, as the sole output of the ions from the RS in a CLS is plant uptake. The gradual increase in Na^+ levels in the RS leads to elevated EC levels that restrict yield due to salinity stress [43,44]. To address this issue, a common practice is partial discharge of DS, which facilitates sodium output from the RS [45,46]. This technique is termed "semi-closed soilless culture system" (semi-CLS). This practice diminishes the environmental sustainability of CLSs and decreases water and nutrient use efficiency, and it is not allowed or is allowed under strict conditions in some northern European countries [14,47].

Controlled exposure of the crop to salinity eustress enhances the fruit quality of many vegetables such as tomatoes [48]. Thus, to obtain high-quality fruit, the standard recommended EC and nutrient concentrations in the root zones of soilless cultivated fruit vegetables are higher than the minimum concentrations required for optimal nutrition to impose salinity eustress [43]. If the Na^+ concentration in the raw water used to prepare NS results in Na^+ accumulation to levels that are not toxic to the plants but only impose salinity stress due to excessively high EC levels, a smart nutrient management strategy can alleviate or even eliminate yield losses. This strategy, which can be commercially applied, is based on the gradual decrease in nutrient input as Na^+ accumulates, thus preventing an increase in EC in the RS [43,45,49]. This strategy accepts higher sodium levels in the RS without a commensurate increase in EC to harmful levels in the RS. Furthermore, this strategy reduces nutrient emissions by lowering the nutrient concentrations in the discharged DS. Maintaining nutrient balance in the root environment is a significant challenge when implementing this strategy. This is necessary to prevent any negative impact on plant growth and yield due to lower nutrient levels in the RS. Adjusting the nutrient supply based on frequent determination of the nutrient and Na levels in the RS (i.e., every fortnight) can ensure optimal crop nutrition.

When equilibrium is achieved between nutrient supply and removal from the system in soilless cultures, the concentration of the i ion in the SS can be described as a function of the concentration of this ion in the DS, the UC of this ion, and the drainage fraction (DF), according to the following equation suggested by Sonneveld (2000) [22]:

$$C_{it} = C_{iu} + a(C_{id} - C_{iu}) \tag{2}$$

where C_{it} denotes the concentration of the i ion in the NS supplied to the crop (SS), C_{iu} denotes the UC of the i ion, C_{id} denotes the concentration of the i ion in the DS, and a denotes the DF ($0 \leq a \leq 1$).

Solving (2) for a renders the following equation:

$$\alpha = \frac{C_{it} - C_{iu}}{C_{id} - C_{iu}} \tag{3}$$

When $i = Na^+$, Equation (3) can be used to estimate the target DF as a function of the maximum acceptable Na^+ concentration in the RS/DS (substituted for C_{id}) if the Na^+ UC (substituted for C_{iu}) that is anticipated for the particular level of C_{id} is known from experimental work [37,50,51]. To estimate the target DF, C_{iu} in (3) should be substituted by the Na^+ concentration in the raw water used to prepare the NSs.

3.4. Technologies Used for Nutrient Solution Preparation in Closed Soilless Systems

In commercial CLSs, the blending of DS with raw water and fertilisers to prepare SS can be performed by applying three alternative technologies, depending on the soilless cropping system. These alternative approaches differ mainly in the sequence of performing two distinct steps during the preparation of the SS for CLSs, i.e., the injection of stock solutions via the FS and mixing with the DS. In addition to the sequence of adding fertilisers and DS when preparing SS, the level of EC control during the whole process also differentiates the applied technical approach. The three alternative technical approaches are illustrated in Figure 2 and are described in more detail in the next section.

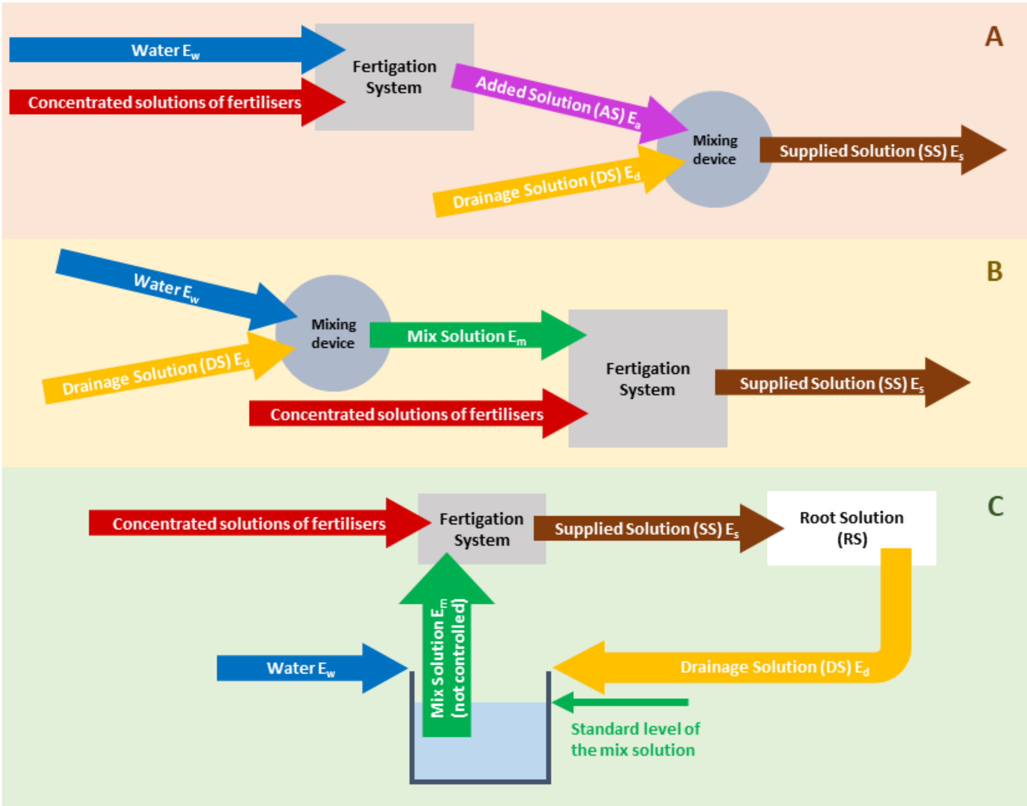

Figure 2. Different approaches for preparing NS for soilless crops when reusing the drainage solution. (**A**) First, the fertilisers are added to water to prepare AS with a target EC (*Eu*); subsequently, the DS is mixed with the AS to prepare SS with a target EC (*Es*). (**B**) First, the DS is mixed with raw water to obtain a mix with a pre-set EC (*Em*); subsequently, the fertilisers are added to this mix to prepare AS with a target EC (*Es*). (**C**) First, the DS is mixed with raw water without controlling the EC of the mix; subsequently, the fertilisers are added to this mix to prepare AS with a target EC (*Es*) [8].

3.4.1. Injecting Fertilisers into Water to Prepare AS with a Target EC (E_a), and Subsequently Mixing the DS with the AS to Prepare SS with a Target EC (E_s)

This approach (Figure 2A) can be applied if the nutrient injection into the system is calculated according to the concept of target concentrations in the SS. According to this technical approach, an automated fertigation system injects stock solutions into the irrigation water, thus preparing the AS. The AS is subsequently blended with DS using a mixing device that automatically adjusts the mixing ratio with the aim of reaching a pre-set target EC in the outgoing SS (E_s). This system is technically simple and understandable both in its technical implementation and in the calculation of the fertiliser needed to prepare stock solutions (or the nutrient injection rates if single-fertiliser stock solutions are used). However, a major drawback of this approach is the difficulty in properly adjusting the pH of the SS because the pH of the DS is usually higher than the target value. Consequently, the pH of the SS may increase to levels higher than the target value when the AS and the DS are mixed.

3.4.2. Mixing the DS with Raw Water to Obtain a Mix with a Pre-Set EC (E_m), and Subsequently Injecting Fertiliser Stock Solutions into the Mix to Prepare SS with a Target EC (E_s)

This technical approach (Figure 2B) is compatible with both concepts, i.e., the target composition of the AS and the target composition of the SS. The concept of a target composition in the SS better matches this technical approach because the fertiliser injection (composition or injection rates of stock solutions) is calculated following similar steps to those performed in open systems. However, the changes in the composition of the DS during the time interval between two determinations of its composition make this concept less reliable than the concept of a target composition of the AS, which involves standard rates of net nutrient supply based on the anticipated uptake concentrations. Therefore, in the commercial application of CLSs, this technical approach (first the input of DS and then the injection of fertilisers) is combined with the concept of a target composition of the AS for the calculation of the fertiliser injection rates.

3.4.3. Mixing the DS with Raw Water without Controlling the EC of the Mix, and Subsequently Injecting Fertiliser Stock Solutions into the Mix to Prepare SS with a Target EC (E_s)

This concept (Figure 2C) is mainly applied in water culture systems (hydroponics). Due to the lack of a porous medium that can retain NS reserves in the root environment in water culture systems, the flow rate of supplied NS is dramatically higher than in substrate-grown crops. As a result, the DS fraction is only slightly lower than 1 and the irrigation of the crop with SS is frequent, if not continuous. Hence, it is much easier and thus more reasonable to initially collect the DS in a tank with a constant level maintained by controlling the inlet of raw water (e.g., using a floater). Since the mixing ratio of DS and water in this tank is controlled by maintaining a constant level and not by adjusting it automatically to achieve the target EC, the EC of the mix is variable, although no substantial fluctuations are anticipated. This mix can be pumped periodically into a fertigation system to inject fertilisers into it, thus maintaining its EC and pH close to preset target values and supplied to the crop either continuously or following a desired irrigation schedule. Furthermore, a similar approach is applied in floating systems, which are also water culture systems. The main tank where the roots are developed contains the RS, and AS is supplied to maintain RS at a constant level. This technical approach is only compatible with the concept of target nutrient composition in the AS.

4. Use of Decision Support Systems to Optimise Fertigation in Closed Soilless Cultivations

The advances in computer and information technologies allowed for the development of efficient decision support systems (DSS) to support plant nutrition and fertilisation in horticulture. A DSS should principally be based on suitable nutritional models and algorithms, which should be fed with credible data on the nutrient requirements of each cultivated species to successfully support crop nutrition. Innovative DSSs, which incorporate the latest state of knowledge, can substantially contribute to restricting NO_3^- leaching and P runoff into water resources due to inappropriate fertilisation practices in agriculture and horticulture [4]. Specially designed DSSs enable precise adjustment of the rates and timing of fertiliser application to levels fully meeting the requirements of the crop, taking into consideration several variables that impact plant nutrition and crop development.

Due to the limited volume of the rooting medium in soilless cultures [52], small deviations between the nutrient supply and the nutrient uptake rates can gradually shift the nutrient concentrations in the root zone to considerably higher or lower levels than the optimum. Thus, the use of suitable DSSs for accurate estimation of the required nutrient supply rates is of primary importance in CLSs to avoid nutrient imbalances in the root zone, hence ensuring high yield potential.

Several DSSs have been developed to support the fertigation of vegetable crops based on modelling and prediction of nutrient uptake. Some of them are aimed at predicting nutrient requirements by simulating crop growth and plant biomass production in combination with input data from regular determination of tissue nutrient concentrations [36,53–56]. Other DSSs are based on the estimation of the nutrient status of the root environment (determination of the DS composition) and the changes recorded during the cropping period due to the uptake of nutrients by plants [37,57,58]. Most of these DSSs deploy models that were either developed to simulate nutrient uptake in crops grown in soil [56,59] or can be used in both soil-grown and soilless crops [36,54,55]. Other DSSs are specific for high-value vegetables like tomatoes or leafy vegetables [60,61]. Only a few DSSs have been developed specifically for soilless cultures [34,62–64]. Another issue is the need for a DSS to cover a wide range of possible combinations of different SCSs and plants, allowing a wide use of DSSs. However, there is hardly any report in peer-reviewed publications on DSSs specifically designed to support the fertigation of crops cultivated in closed-loop soilless crops. Another serious problem with the use of DSSs to support precise fertilisation of vegetable crops is that most of the available DSSs are used either locally or by private companies to support their clients. Consequently, accessibility to credible DSSs that can support growers with tailoring fertiliser supply to current plant needs, thus minimising nutrient losses and environmental pollution, is currently a challenge.

The DSS NUTRISENSE has been developed by the Laboratory of Vegetable Production of the Agricultural University of Athens to bridge this gap by providing a tool to optimise nutrient management in soilless cultures. NUTRISENSE, which is available online via the link https://nutrisense.online/ (accessed on 13 November 2023), is described in more detail in the next section.

5. NUTRISENSE as a DSS for Optimising Nutrient Management in Closed Soilless Crops

5.1. The General Concept of NUTRISENSE

The version of NUTRISENSE that is currently available online at https://nutrisense.online/ (accessed on 13 November 2023) has been designed for use mainly in open and closed-loop SCSs, although it can also be used in soil-grown crops.

This version of NUTRISENSE is used to calculate NS based on desired characteristics given as target values and readjusted during the cropping period after chemical analyses of the RS and DS. NUTRISENSE utilises standard recommendations on the nutrient requirements of a wide variety of vegetables and ornamental plant species obtained from various sources in the literature which have been placed in a database. When NUTRISENSE is used to compute NS for a particular crop, the recommendations included in the database are adapted to the specific characteristics and conditions of this crop. More specifically, NUTRISENSE takes into consideration the following crop characteristics when an NS recipe for a crop is requested:

- crop species,
- season of the year,
- plant development stage,
- mineral composition of the raw water used to prepare the NS,
- available fertilisers,
- number and volume of stock solution tanks
- specific characteristics of the available equipment for fertigation.

The core of DSS NUTRISENSE is a largely extended version of the algorithm proposed by Savvas and Adamidis [65]. However, the current version incorporates many additional elements conferring extensive capabilities, which are presented in two recent papers [4,63]. One of the most important components included in this software to feed the extended version of the algorithm initially developed by Savvas and Adamidis [65] is a database with standard NS compositions for different crop species, developmental stages (e.g., vegetative or reproductive), and soilless culture systems (open or closed-loop systems). This database includes a complete set of data for all important greenhouse crops, originating from several literature sources (see [4] and publications therein). Another novel component of NUTRISENSE is an algorithm used to automatically readjust the composition of the currently used NS after the addition of the DS composition to the software [4].

The available options on the type of NS calculated by NUTRISENSE are:

- starter NS (used to moisten the substrates or to fill up the tanks in water culture systems before planting),
- standard NS for an open SCS,
- standard NS for a closed-loop SCS,
- readjusting the NS composition in an open SCS,
- readjusting the NS composition in a closed-loop SCS.

If the selected type of NS is "readjusting the NS" (both in open and closed-loop systems), the user also has to introduce the composition of the currently used NS and the current composition of the DS as determined by a recent chemical analysis. To maximise the benefits of NS readjustment with NUTRISENSE, the time between the collection of a DS sample and the application of the readjusted NS formula should be as short as possible.

After the introduction of this information into the NUTRISENSE portal, the user only has to request the calculation of a new NS formula by clicking on "calculate NS formula" and the software immediately provides a full set of recommendations as output. The major components of this output are (i) the composition of the calculated NS, particularly EC, pH, nutrient concentrations (mmol L^{-1} for macronutrients and μmol L^{-1} for micronutrients), and molar mutual ratios, and (ii) full instructions for the preparation of SSs and their injection into water in the fertigation system used to prepare the final NS supplied to the crop. The mutual ratios in the NS calculated by NUTRISENSE (on a molar basis) are K:Ca:Mg, N/K, and NH_4-N/total-N.

It is important to note that in open SCSs, the calculated NS is the SS, while in CLSs, the calculated NS is the AS, provided that the crop's nutrition is not controlled using ISEs. However, in CLSs operated with ISEs, the NS calculated by NUTRISENSE is the SS.

The FS works by diluting two concentrated solutions (CSs) of fertilisers and a CS of acid for pH adjustment (A/B FS). While the DS is not recycled, NUTRISENSE calculates the exact masses of fertilisers to be added to the specified volume of water to prepare the CSs. If an A/B FS is used in a CLS, NUTRISENSE calculates not only the masses of fertilisers needed to prepare CSs but also the EC of the solution obtained when the recycled DS is mixed with irrigation water. If a multi-tank fertigation system is used (a separate CS for each fertiliser), NUTRISENSE calculates the relative injection ratio of each fertiliser, which has to be introduced into the controlling system of the FS. Furthermore, NUTRISENSE can be additionally used to specify the optimal masses of fertiliser needed to prepare each CS, thus contributing to a more accurate injection of all CSs into the water when fresh NS is prepared.

5.2. Readjustment of the NS Formula

The standard recommendations for the optimal compositions of SS or AS found in literature sources are general estimations of the true nutrient requirements of a crop species. However, the exact nutrient requirements of a particular crop are rarely identical to those suggested in the literature because different crops grow under different conditions. Even small deviations between the standard recommendations and the true nutrient requirements of the plants are additive over time and may gradually result in substantial nutrient imbalances. To avoid the occurrence of nutrient imbalances in the RS, the composition of the SS in open systems or the AS in CLSs is frequently readjusted to more precisely match the actual plant uptake rates. To achieve this goal, NS samples are frequently collected (optimally at fortnight intervals) either from the root zone or the drainage, and their mineral composition is determined using analytical procedures conducted in a credible chemical laboratory. The results of the chemical analysis are immediately introduced into the NUTRISENSE, which subsequently provides a readjusted composition of the NS formula.

To readjust the composition of the AS supplied to a CLS, NUTRISENSE uses a novel algorithm based on mass balance equations. This algorithm calculates the actual UCs of the crop for an interval between two consecutive chemical analyses of the DS [4]. The UC of each nutrient is calculated by taking into consideration (a) the difference in the mass of each nutrient in the RS–DS at the beginning and the end of the interval, and (b) the added mass of this nutrient via the AS during this interval. The estimated UCs, which were obtained using data on the time interval between the last (n) and the previous ($n - 1$) date of DS sampling, are assumed to also be valid for the next time interval (from the n^{th} to the $n^{th} + 1$ sampling date). Any discrepancies will be compensated for in the next readjustment of the AS. The aim of the readjusted AS is to maintain or restore the nutrient concentration to the target value. Thus, NUTRISENSE calculates the readjusted AS by adding or subtracting a correction factor to or from the UC, respectively, if the level of a nutrient in the RS is lower or higher, respectively, than the target concentration. NUTRISENSE also incorporates an algorithm to compensate for Na^+ accumulation. The algorithm is based on the gradual reduction of the target nutrient concentrations in RS to levels equivalent to the Na^+ increase while maintaining their mutual ratios and the EC.

The readjusted AS formula includes new target values for EC, pH, and nutrient concentrations, as well as the masses of fertilisers needed to prepare CSs for this AS or the injection rates of each CS when single fertiliser CSs are used. A schematic representation of the algorithm used to readjust the AS in CLSs is presented in Figure 3.

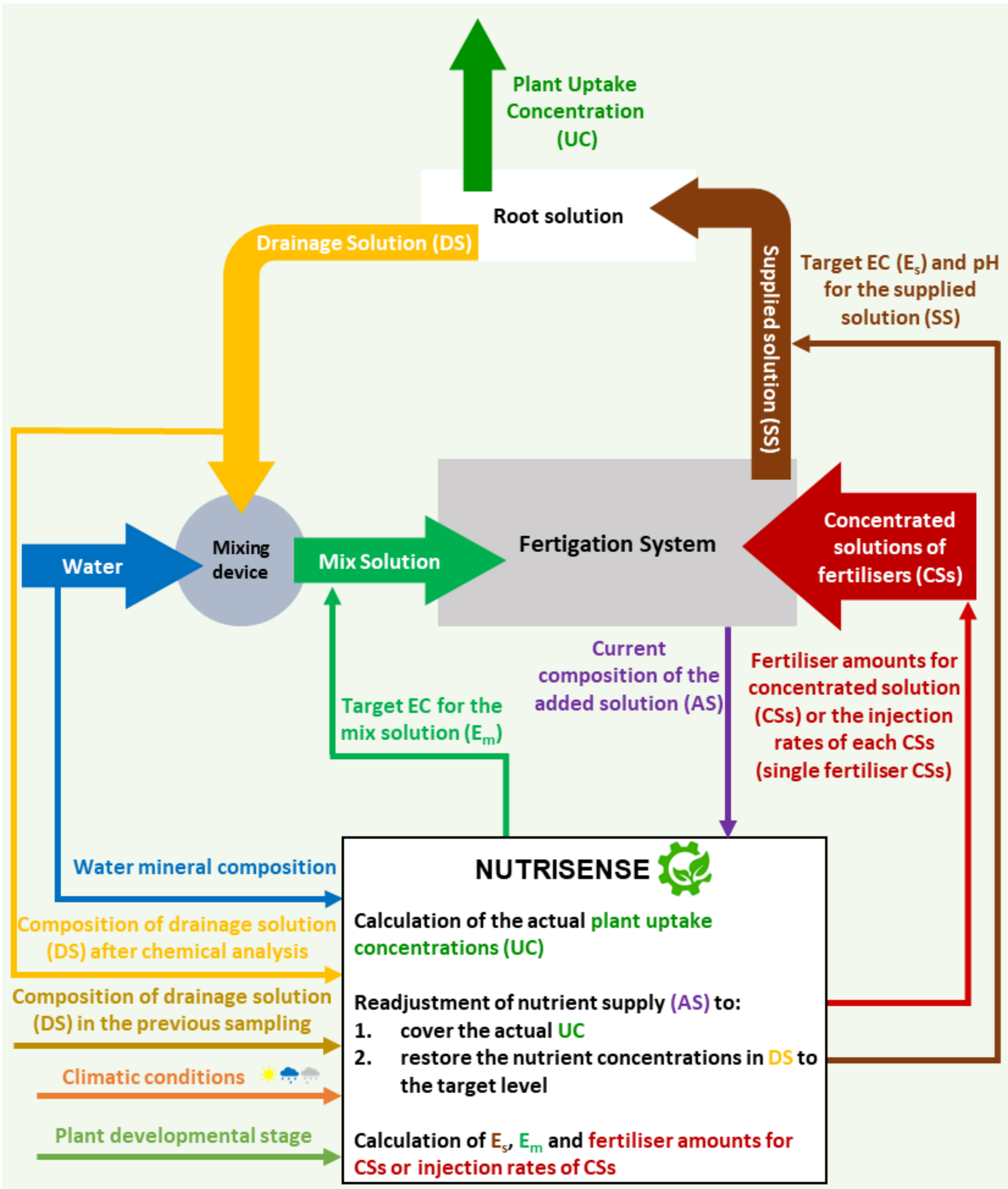

Figure 3. Schematic outline of the calculations needed to readjust the nutrient supply in a CLS using the DSS NUTRISENSE. The data input for the DSSs are plant development stage, mineral composition of the irrigation water, chemical analysis of the current and previous DSs, mineral composition of the currently applied AS, and climatic conditions. The output of the DSS is the readjusted composition of the AS, including the target EC for the mix of raw water and drainage solution, target EC and pH for the SS, amounts of fertilisers needed to prepare the respective CSs, or injection rates of each CS when single fertiliser CSs are used.

5.3. Use of Ion Selective Electrodes with NUTRISENSE for Smart Fertigation Management

The standard commercial practice in soilless greenhouses is to send a DS sample to a laboratory 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 the AS in CLS is readjusted. However, the results of a laboratory analysis are often received several days after the collection of the DS sample. Therefore, in-situ measurements of individual nutrient concentrations in the DS would improve the efficiency of nutrient management in CLSs. Ion-selective electrodes (ISEs) can estimate the concentration of a single ion in a multi-ion aqueous solution, such as a DS because they have an ion-selective membrane that responds specifically to one analyte in the presence of other ions in the solution [66]. Moreover, ISEs have practical advantages such as simple use, wide measurement range, and rapid and direct measurement, without any need for dilution or addition of reagents for colour development, which is the case with colorimetric and refractometric determination methods [67,68]. In this regard, they are attractive tools for daily or real-time estimation of DS composition in combination with an EC and a pH meter. Several publications have, in the last few years, presented data on portable, manual, or automated ISE systems for application in a soilless culture that claims acceptable accuracy [67,69–72]. However, the use of ISEs is still at an experimental level and their adoption by commercial greenhouses is currently scarce.

An important aspect for maximising the anticipated benefits from the use of ISEs in CLSs is the online processing of data obtained using suitable software. Such software should take into consideration not only the mathematical models and engineering background of the ISEs but also the complex chemistry of the NS and its interconnection with the nutrient requirements of plants grown in SCSs. NUTRISENSE incorporates a unique algorithm to support the use of ISEs for precise plant nutrition in CLSs.

6. Conclusions

The adoption of CLSs reduces the use of irrigation water by 20–35%, depending on the applied DF, and fertiliser consumption by more than 40–50%, thus avoiding the pollution of water resources and increasing crop profitability. Novel DSSs such as NUTRISENSE can be used as effective tools for easy and accurate readjustment of the nutrient supply in soilless greenhouse crops. A suitable DSS for this purpose can be complex in its background but should be simple and friendly in its operation so that it can be used effectively not only by experts but also by growers with hardly any background in chemistry and mathematics. To address the problem of Na^+ and Cl^- accumulation in the RS of CLSs when they occur at suboptimal concentrations in raw water, the increase in their concentrations in the root zone of the crop can be compensated for by gradually reducing the target macronutrient concentrations. Thus, the EC in the RS can be maintained within an acceptable range that does not restrict the yield potential of the crop. NUTRISENSE proved to be a suitable DSS for controlling plant nutrition in commercial crops grown in closed-loop soilless systems. Recent research has shown that the use of a DSS such as NUTRISENSE in CLSs can maintain optimal nutrient levels in the RS, thus minimizing or even eliminating the need to discharge DS. Consequently, considerable amounts of precious water and fertilisers can be saved, while the pollution of water resources by N and P emissions can be prevented without compromising crop yield.

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Abbreviations

DSS	decision support system
SCS	soilless culture system
CLS	closed-loop soilless culture system
NS	nutrient solution
AS	added solution
SS	supplied solution
UC	uptake concentration
RS	root solution
DS	drainage solution
DF	drainage fraction
CS	concentrated stock solution of fertilisers
FS	fertigation system
ISE	ion-selective electrode
Symbols	
E_w	is the EC (dS m^{-1}) of the raw water
E_m	is the target EC (dS m^{-1}) of the blend of DS and raw water
E_u	is the estimated EC (dS m^{-1}) of the UC
E_a	is the target EC (dS m^{-1}) of the AS
E_s	is the target EC (dS m^{-1}) of the SS
E_d	is the EC (dS m^{-1}) in the RS and DS

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