horticulturae

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Performance Evaluation of a Cascade Cropping System

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Abstract: Minimum environmental impact and improved resource efficiency is attainable for soilless cascade systems where the nutrient solution drained from a primary (donor) crop is reused to fertigate a secondary (receiver) crop. However, it is not clear whether the nutrient solution drained from the primary crop can completely satisfy the needs of a secondary crop and if the productivity of the secondary crop is compromised. To test this hypothesis, a prototype soilless cascade system was developed and evaluated. To assess the performance of the system in terms of yield, water and nutrient productivity, a tomato crop was used as the primary crop, while lettuce, spinach and parsley were tested as secondary crops under different drainage management strategies. Measurements of plant growth, crop fresh and dry matter production, leaf chlorophyll and nutrient content, and photosynthesis rate were performed in the secondary crops. In addition, the water productivity and nutrient use efficiency for the fertigation of the primary and secondary crops were recorded. The results showed that the yield of the cascade spinach crop increased by up to 14% compared to the control treatment (monoculture of secondary crop fertigated by standard nutrient solution). The yield of the lettuce and parsley crop was not affected by the reuse of the tomato crop drainage solution. The water productivities of the lettuce, spinach and parsley plants fertigated with pure drainage solution were 50%, 30% and 14% higher than in the control treatment, respectively. The nitrogen and phosphorus use efficiency was improved by more than 50% compared to the control treatments.

Keywords: multi-cropping; drainage management; water use efficiency; nutrient use efficiency

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Citation: Karatsivou, E.; Elvanidi, A.; Faliagka, S.; Naounoulis, I.; Katsoulas, N. Performance Evaluation of a Cascade Cropping System. *Horticulturae* **2023**, *9*, 802. https://doi.org/10.3390/horticulturae9070802

Academic Editors: Nazim Gruda, Rui Manuel Almeida Machado and Erik van Os

Received: 10 June 2023
Revised: 5 July 2023
Accepted: 11 July 2023
Published: 13 July 2023

1. Introduction

In greenhouses, closed soilless cultivation systems provide the opportunity to increase the water and nutrient use efficiency and reduce the environmental impact of the cultivation system through the reuse of the drained water and nutrients [1,2]. However, due to the low quality of the water used in the Mediterranean countries (high concentrations of Na^+ and Cl^-, but also high Ca^{2+}, Mg^{2+}, and SO_4^{2-}, [3]), completely closed soilless systems are not feasible. Appropriate management of the drainage solution (DS) using suitable practices and models may reduce the need to discharge the drainage solution to the environment. To this end, Katsoulas et al. [1] developed a model for automatic drainage solution management in tomato crops grown in semi-closed systems. Nevertheless, partial discharge of the drainage nutrient solution when the levels of electrical conductivity (EC) or of the toxic ions in the system are reached, is still a necessity in these systems.

Many growers in the Mediterranean region operate their soilless systems as open systems, mainly because they do not have the knowledge or the capacity to manage nutrient solution drainage. One of the serious problems of open systems is the effluence of overdosed nutrient solutions from the system into the environment, resulting in eutrophication of soil and groundwater. Abd-Elmoniem et al. [4] showed that the average water consumption of plants grown in open systems was 15% to 17% higher compared to those grown in closed systems. The absolute values of water consumption in lettuce were 68.5 L and 80.5 L per plant for closed and open systems, respectively. Rufi-Salis et al. [5]

reported that closed soilless systems reduce daily water and nutrient consumption by 40% and 35–54%, respectively, when compared to open systems in green pea production. Méndez-Cifuentes et al. [6], in a similar study, concluded that 53 L and 22 L of nutrient solution were required in closed and open systems, respectively, to produce 1 kg of tomatoes. Therefore, open systems consumed 86% more water. Fayezizadeh et al. [7] found that closed systems allowed water and nutrient savings of up to 97% compared to open systems. Closed systems are therefore preferable in terms of reducing environmental pollution.

Sustainable management strategies for the reuse and discharge of DS in closed systems are needed. One of the potential strategies for enhancing the circular economy concept in the context of soilless systems is the development and implementation of soilless cascade systems. In these systems, the drainage of a primary donor crop is utilised for the fertigation of one or more secondary receiving crops that possess a higher tolerance to salinity. The reuse may also continue, with the drainage from the secondary crop being utilised for the fertigation of a tertiary, highly salinity-tolerant crop.

Some pioneer studies on cascade fertigation systems were performed more than 10 years ago [8,9]. Some interesting systems have already been developed, mostly in open-field crops, such as the system developed in San Joaquin Valley in California. However, it is not so easy to manage the drainage solution in these systems, since the solution drains directly into the underlying soil. García-Caparrós [10] studied a pilot cascade system in the facilities of the University of Almeria in Spain, in which the drainage solution from melon cultivation was used to cover the needs of rosemary, with encouraging results.

However, the recent advancements in drainage management and the increased need for sustainable production systems with low environmental impact have increased the interest in further research on soilless cascade systems [5,11–17]. In addition to their excellent utilisation of drained water and nutrients, cascade systems may lead to improvements in the quality characteristics of secondary and tertiary crops due to the increased salinity levels in the system. Incrocci et al. [8] showed that fruit dry matter increased, while Avdouli et al. [11] showed that the content of several compounds associated with the organoleptic, nutritional and nutraceutical qualities of many fruits and leafy vegetables increased when they were cultivated as secondary crops in a cascade system. Nevertheless, the efficient management of a cascade system requires knowledge of the salt tolerance levels [17] and of the fertigation needs of the crops in the loop. Furthermore, the drainage solution of a crop may include phytotoxic root exudates [10] or other metabolites, and may impose recirculation plant protection products [16] in the system. However, advanced cascade research needs to focus on the yield quality of secondary and tertiary crops, and to date, there are scant scientific articles referring to this concept.

Additionally, to obtain a sufficient cascade system, optimal management may require correction with respect to pH, EC and macronutrients, since the drained solution may have abnormal mutual nutrient ratios. However, it is not clear whether the drainage solution collected from the main soilless greenhouse crops can be directly utilised for the fertigation of secondary and then tertiary crops. Moreover, it is not clear which management practices are needed in order to fulfil the fertigation needs of secondary and tertiary crops while increasing the water and nutrient use efficiency of the cascade system.

The aim of this work is to test whether some common leafy vegetables (lettuce, spinach and parsley) can be used as secondary receiving crops in soilless cascade systems with tomato as the primary crop in greenhouses in the Mediterranean region. The specific secondary crops selected for testing were chosen due to their high consumer demand, short cultivation cycle, high nutritional value, flexible growth adaptation to soilless facilities [18–20] and high salt tolerance and ability to accumulate sodium as an osmoregulating resistance mechanism [21]. In this sense, lettuce, spinach, and parsley plants were cultivated under different cascade systems.

In this study, we aim to provide knowledge about the progress of the nutrient concentrations in the different parts of cascade systems and on the utilisation/absorption of different nutrients in soilless cascade systems. The amount of water irrigated to, uptaken by and drained from the plants is also presented. Additionally, yield characteristics (plant height, number of leaves, chlorophyll content index, and photosynthesis rate) of the secondary crops are reported. The evaluation of the different cascade systems was performed on the basis of water productivity (WP) and fertiliser use efficiency (FUE) calculations. With this research, the gap in scientific knowledge with respect to the secondary crop response in cascade systems is decreased.

2. Materials and Methods

2.1. Greenhouse Facilities and Cascade System Set Up

The cascade system was installed in a gothic multitunnel greenhouse belonging to the University of Thessaly, located in Velestino, Central Greece (Latitude 39°22′, longitude 22°44′ and altitude 85 m). The greenhouse was oriented north–south, and the total ground area was 1500 m^2, separated into six compartments. The first compartment was used to host the fertigation and control equipment. Four out of the other five compartments were used for cultivation purposes in this work. In each of the culture compartments, six channels, 20 m in length, and carrying 19 rockwool slabs each (Grodan Delta, NL 100 × 15 × 7.5 cm, 0.18 g cm^{-3}, 90% water retention capacity, Roermond, The Netherlands), were installed.

All the compartments were covered by a polyethylene film in the roof, while the side walls were covered by polycarbonate sheets. Each compartment was further equipped with a roof vent, a pad and fan system, and a thermal/shading screen, and all the systems/compartments were controlled by a climate control computer (SERCOM, Automation SL, Lisse, The Netherlands). The roof vent was opened when the air temperature within the greenhouse was higher than 20 °C or the relative humidity exceeded 87%. The pad-and-fan system was in operation whenever the air temperature inside the greenhouse was higher than 26 °C. The shading screen was used when the outdoor solar radiation was higher than 750 W m^{-2}. The transmittance coefficient of the cover material was 0.75, while the screen's transparency was 0.50.

Within the hydroponic head (500 L), the nutrient solution (NS) was made by mixing different amounts of nutrients, stored within five stock solution tanks (capacity of 120 L each), with tap water or drainage solution (DS). The amounts of nutrients and water or drainage solution used for the preparation of the NS were based on the desired targeted concentration. The system can prepare five different recipes, stored in different nutrient storage tanks (capacity of 500 L) each time. In the current research, two nutrient solution tanks were used for irrigating the primary crop and two for the secondary crops. Therefore, each of the solution tanks was linked with its own injection pump, thus making it possible to automatically prepare fresh NS separately for each crop level (primary, secondary and tertiary). This operation was accomplished by the fertigation system, which generally works using volumetric or electronic injectors. The quality of raw water is a key factor, and must be known from the outset in order to check whether the water can be utilised as is, or if it needs specific treatment in order to calculate the amount of fertilisers required for the preparation of the nutrient stock. When the nutrient solution had reached the optimum concentration values set by the operator, it was transferred from the mixing tank to one of the eight irrigation tanks. The reused NS was first disinfected using a UV-light disinfection system before being supplied to the plants. Figure 1 presents a schematic diagram of the system.

The nutrient solution drained from the crops was collected in the DS tanks. In each culture compartment, two drainage tanks with a capacity of 300 L were used. In the compartments of the secondary crops, the DS was collected in four tanks with a capacity of 100 L, individually for each treatment, before ending in the final tanks (Figure 1). The pH of each NS preparation was set at 5.8. Correction was performed through the addition of NO_3 solution. Through this setup, each compartment of the secondary crop could host two different crop species (two channels 10 m in length), fertigated by two different treatments (two sets of three channels/repetitions). The final DS collected was further reused in the process of preparing a fresh nutrient solution.

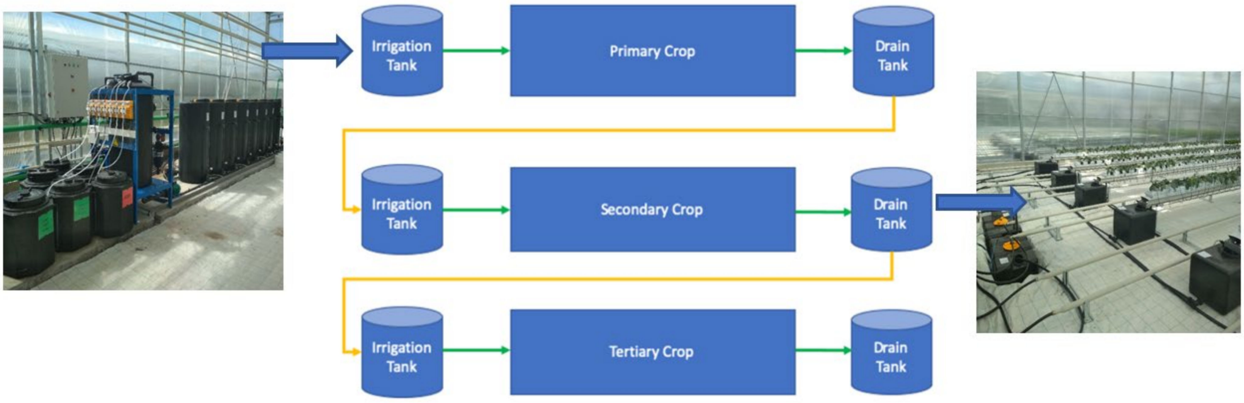


Figure 1. Scheme of the cascade system setup and the flow of the nutrient solution from the irrigation to the drainage tanks. The system is designed to operate in three consecutive circulation levels, but only the first two were used in the present work.

2.2. Crop Management and Experimental Setup

The experiments were carried out from March 2019 to October 2019. Tomato plants (*Solanum lycopersicum* cv. Elpida, hybrid F1) were cultivated to serve as the primary crop in two compartments of the greenhouse. The tomato plants were transplanted in a density of 3 plants m^{-2} at the stage of five extended leaves and 25 cm height. The plants were transplanted on the 29 March 2019, while the cultivation period lasted for six months.

The NS drained from the tomato crop was used for the fertigation of the secondary crops, which were cultivated in two experimental periods. The first period occurred during the vegetative stage of tomato crop, from April to May. During that period, spinach (*Spinacia oleracea* cv. Matador) and lettuce (*Lactuca sativa* cv. Batavia, type iceberg) were cultivated at a density of 4 plants m^{-2}. The plants were transplanted at the stage of three true leaves, 19 days after transplanting of the primary crop (DATp). Their cultivation cycle lasted 42 days. The second period occurred during the fruit stage of the primary crop, from August to October. During that period, parsley (*Petroselinum crispum* cv. Mill.) was cultivated at a density of 4 plants m^{-2}. The plants were transplanted at the stage of two true leaves, 137 DATp. The cultivation cycle of the parsley crop lasted 54 days. The cultivation cycle of each secondary crop corresponds, according to local practice, to that of a commercial production. The time interval between the two experiments (June–July) was used to clean the irrigation system and change the cultivation of the secondary crop, so no data were recorded.

To achieve a randomised block design for the secondary cultivation, in each of the six lines of each compartment, 36 plants of each species were cultivated (4 plants per slab; 72 plants per line; 432 plants per species in total). In each secondary crop, in both periods, a total of four irrigation treatments were applied in three repetitions (36 plants per treatment and repetition), in which the plants were supplied with: (i) fresh nutrient solution (FS) comprising the control treatment (T1 treatment: 0%DS + 100%FS); (ii) drainage solution of the primary crop diluted with water (W) at a ratio of 50–50 (T2 treatment: 50%DS + 50%W); (iii) drainage solution of the primary crop diluted with water at a ratio of 75–25 (T3 treatment: 75%DS + 25%W); and (iv) drainage solution of the primary crop without any dilution (T4 treatment: 100%DS + 0%W). In all systems of secondary crops, the drainage was collected, but was not recycled, in order to simulate the conditions of an open-loop system.

The tap water used for the NS preparation had a pH of 7.1, an EC of 0.8 dS m^{-1} and an Na^{+} concentration of 1.3 mM L^{-1}. The composition of the nutrient solution used for both the primary and secondary crops was similar to that applied in Mediterranean climatic conditions, and was modified according to the plant stage. The pH, EC set points and nutrient composition supplied to the crops according to their growth stage are shown in Table 1. The irrigation dose for the primary crop was set to cover at least the 30% of the leaching fraction. The daily dose for the secondary crop was around 0.345 L per plant in lettuce and spinach and 0.199 L per plant in parsley. The amount of water was added in the NS supplied to the secondary crop, and the pH and EC value variations according to the treatment are reported analytically as results.

Table 1. The targeted nutrient composition, pH and electrical conductivity (EC) of the nutrient solution supplied to the plants of primary and secondary crop according to growth stage.

Parameter	Unit	Primary Crop Vegetative Stage	Primary Crop Fruit Stage	Secondary Crop Vegetative Stage
pH		5.8	5.8	5.8
EC	(dS m^{-1})	1.3–3.5	1.3–3.5	2.2–2.6
Ca^{+2}	(mM L^{-1})	4.1	3.1	4.8
Mg^{2+}	(mM L^{-1})	2.0	2.0	1.9
K^{+1}	(mM L^{-1})	4.5	3.1	6.5
NO_3^-	(mM L^{-1})	9.5	8.2	12.9
NH_4^+	(mM L^{-1})			0.3
H_2PO_4	(mM L^{-1})	0.6	0.4	1.1
Fe	(μM L^{-1})	17.4	17.1	15.0
Mn	(μM L^{-1})	3.8	1.7	2.9
Zn	(μM L^{-1})	5.9	1.3	2.8
Cu	(μM L^{-1})	0.7	0.6	0.8
B	(μM L^{-1})			30.0
Mo	(μM L^{-1})			0.5

2.3. Measurements

Air temperature (Ta, in °C) and relative humidity (RH, in %) were measured using a temperature–humidity sensor (model HD9008TR, Delta Ohm, Italy), which was calibrated before the experimental period and placed 1.8 m above ground level. The irradiance (Rg, i, in W m^{-2}) inside the greenhouse was recorded using a solar pyranometer (model SKS 1110, Skye instruments, Powys, UK) located 1.8 m above ground.

Plant height, number of leaves, and chlorophyll content index were obtained in the plants of the secondary crop twice a week. Plant height (H) was measured by placing a calibrated ruler on the top edge of the slab and measuring to the tip of the last open leaf of the plant (number of samples (n) = 30 per treatment). The number of leaves was measured for 30 plants per treatment. Chlorophyll content index (CCI) was recorded using non-destructive sensing by means of an Opti-Science sensor, performing measurements in contact with the leaf (CCM 200, Opti-Science, Hudson, NH, USA). CCI index is the ratio of the chlorophyll's reflectance in the NIR band over the reflectance in the red band. The measurements were performed in young and fully developed leaves during the morning to avoid the effect of direct sunlight on the chlorophyll meter (n = 10 per treatment).

Photosynthesis rate (P_N) (μmol CO_2 m^{-2} s^{-1}) was measured weekly in young and fully developed leaves (n = 5 per treatment) using a portable photosynthesis system (LCpro+ 1.0 ADC, Bioscientific Ltd., Hoddesdon, Hertfordshire, UK).

Two destructive samplings were performed during both periods in order to estimate the fresh matter (FM), dry matter (DM) and nutrient leaf content for each secondary crop. During the first period, destructive sampling was performed 15 and 42 days after each secondary crop had been transplanted (DATs), and in the second period, 36 and 54 DATs (n = 9 per treatment). The samples were dried in a forced-air oven for 72 h at 70 °C. The data were initially calculated in kg $plant^{-1}$ and subsequently adjusted in kg m^{-2}. Total yield of the primary crop was also measured at the end of the seven-month cultivation period to estimate the total biomass expressed in kg m^{-2}.

Dried samples of parsley plants were subsequently ground to powder in order to perform mineral analyses of the main macro-micronutrients (N, P, K, Ca, Mg, Fe, Zn, Mn and Cu). In total, 36 plants per destructive process were used to determine the uptake nutrient concentrations of each secondary crop. The extraction was performed using the Kjeldahl Nitrogen method (TKN) based on the Kjeldahl protocol [22]. Nutrient elements were determined by ICP (ICP-OES, SPECTRO Analytical Instruments GmbH, 180 Kleve, Germany).

EC (dS m^{-1}) and pH values of the irrigation and drainage solution (IS) were measured automatically with sensors (type GPHU 014 MP-BNC, Greisinger, Regenstauf, Germany) placed within the hydroponic head tank. The volume (V, L) of the drained nutrient solution was automatically recorded using water pressure gauges (Klinkerbeg, Graben-Neudorf, Germany) placed in each drainage tank. Furthermore, during the second period, samples of the irrigation (IR) and drainage (DR) solution were collected manually for quantitative assessment of NO_3, P, K, Ca, Na, Mg, Fe, Zn, Mn and Cu content on two sampling dates (DAT 36 and DAT 54). Extraction was performed using the Kjeldahl Nitrogen method (TKN) based on the protocol described by Kjeldahl [22], while the nutrient elements were determined by ICP (ICP-OES, SPECTRO Analytical Instruments GmbH, Kleve, Germany).

2.4. Calculations

The daily and nightly average Ta and RH were calculated for the periods from 6:00 to 18:00 and from 18:00 to 6:00 (local time), respectively, during the respective cultivation period of primary and secondary crops.

In the primary crop, the total volume of NS applied (V_{IR}), expressed in L m^{-2}, was the sum of the volume of water added in each irrigation event (L) for a six-month cultivation period divided by the total cultivated area (m^2). The total volume of NS drained (V_{DR}) from the plants (L m^{-2}) was the sum of the volume drained after each irrigation event for a six-month cultivation period divided by the total cultivated area (m^2).

In the secondary crops, the V_{IR} and V_{DR} data were adjusted in the primary crop cultivation period. To achieve this, the total volume of each secondary crop was divided by the number of the days in each cultivation period, and then multiplied by the number of days for which the primary crop was cultivated. Here, the data for water and primary crop DS added during NS are presented separately. The total volume uptaken (V_{up}) by the plants consists of the amount applied minus the amount drained from the plants. To evaluate the final impact of each system to the environment, the above data for both primary and secondary crop are summarised.

The crop uptake concentration (C_{up}), defined as the amount of nutrient absorbed by the plants, was estimated based on the following equation:

$$C_{IR} \times V_{IR} + C_{up} \times V_{up} = C_{DR} \times V_{DR}, \quad (1)$$

where (C_{IR}) and (C_{DR}) correspond to the concentration of the nutrient element in the irrigation and drainage solutions, respectively, expressed in mg L^{-1}.

The cumulative volume irrigated to and drained from the crop throughout the whole cultivation period for each crop and treatment was used in order to determine the water productivity. The water productivity (WP, in kg m^{-3}) and the fertiliser use efficiency (FUE, in kg kg^{-1}) of the primary and secondary crops were estimated by dividing the total yield FM (which is the sum of the primary and the secondary crop) with the total volume of the fresh water or fertiliser applied over the six-month cultivation period. Similarly, the nitrogen (NUE) and phosphorus (PUE) use efficiency were calculated by dividing the sum FM by the total amount of nitrogen or phosphorous added, adjusted to the six-month cultivation period. The total amounts of nitrogen and phosphorus were calculated by multiplying the N and P content showed in Table 1 by the V_{IR}.

2.5. Statistical Analysis

Comparison of means was performed by applying one-way ANOVA at a confidence level of 95% ($p \leq 0.05$) using SPSS (Statistical Package for Social Sciences, IBM, Armonk, NY, USA). Additionally, least significant difference (LSD) at the 5% level of significance was used to determine whether the drainage solution management affected the quality (yield) and quantity (marketable products) of the production. The mean values and standard deviations (±SD) of the measured parameters are reported.

3. Results

3.1. Climatic Conditions

The average daily air temperature and relative humidity in the cultivation area of the tomato crop were 21 °C (with standard deviation SD ± 4.0) and 63% (SD ± 18), respectively. In the compartments of the secondary crop, the respective average values were 22 °C (SD ± 4.1) and 53% (SD ± 19), respectively. The respective maximum and minimum daily average values measured were 26.5 °C and 18 °C and 75% and 50%, respectively. During the night, the values remained stable at around 15 °C (SD ± 3.9) and 75% (SD ± 19) for both primary and secondary crops. The maximum outdoor global radiation was around 1000 W m^{-2} (SD ± 280), and the daily mean radiation varied around 420 W m^{-2}. The daily mean radiation inside the greenhouse was around 315 W m^{-2}, indicating an average transmission of the greenhouse to solar radiation of about 75%. The consistent daily climatic conditions occurred across all the treatments had no significant impact on the assessment of the results.

3.2. Nutrient Solution Quality

To assess the NS quality, it is necessary to examine the status of EC and pH at each stage of the system. As already mentioned, the EC values of the NS supplied to the tomato crop varied from 1.3 to 3.5 dS m^{-1} over the total cultivation period (Table 1). The values were changed according to the growth stage of the crop, where at the vegetative stage the values were higher than at the fruit stage. The EC values of the DS were about 30% higher than those of the NS supplied. Similar to the EC, the pH values increased from 5.8, recorded in the supplied NS (Table 1), to more than 6.2, and up to 7.4 (SD ± 0.7). Comparable progress was observed in the EC and pH values of the secondary crop control treatment (T1 treatment) during both periods.

For the other cascade treatments, the EC and the pH values were changed according to the quality of the DS of the primary crop and the amount of water added in the NS preparation process. At the primary crop vegetative stage (first period), where the EC values of the NS supplied were high, the respective values of the cascade treatments were also high, and were higher than those of the control treatment ($p < 0.05$). Only the values of the T2 treatment were lower than those of the control treatment ($p < 0.05$). At the primary crop fruit stage (second period), where the EC values of the NS supplied were low, the three cascade treatments demonstrated values lower than the control ($p < 0.05$). Similar to the primary crop, the EC values of the DS increased by about 30% and the pH values increased from 5.8 to more than 6.2.

The above data of EC variation in the NS supplied to and drained from the plants are presented in Figures 2 and 3, according to the treatment received by each secondary crop. The pH variations of the DS according to the respective treatment are presented in Figure 4. The pH values in the supplied NS are not presented, since the pH was set at 5.8 for each treatment.

3.3. Water Consumption

The total volumes of NS supplied to and drained from the primary crop during the six-month cultivation period were 882 L m^{-2} and 472 L m^{-2}, respectively. In the secondary crop, an amount of water and DS was added to the total amount of the supplied NS, changed according to the treatment and for each cultivation period. However, in order to be able to compare the treatments and their efficiency, the secondary crop data of the NS supplied to, uptaken by and drained from the plants were adjusted to a six-month cultivation period, equal to that of the primary crop. The resulting data are presented in Table 2.

According to the adjusted calculations, as was expected, the maximum amount of primary crop DS reused was observed in the T4 treatment. In this case, and for the same cultivation period with tomato, 290 L m^{-2} was reused to irrigate the lettuce plants. The same amount was reused in spinach plants, while in parsley plants, the amount was

167 L m^{-2}. For the other cascade treatments, the amounts of primary crop DS reused were 50% and 75% lower than the T4 treatment under T2 and T3, respectively.

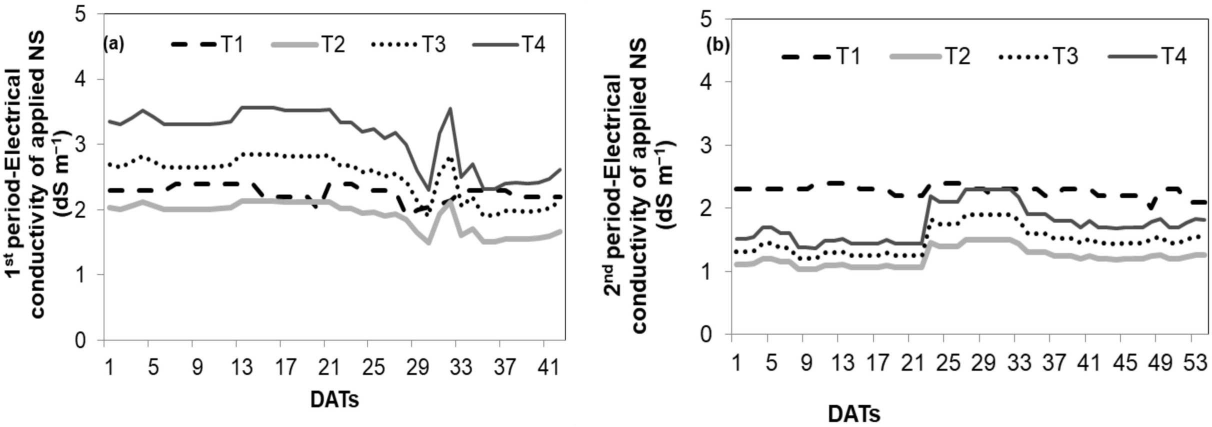


Figure 2. Evolution of EC values of the NS supplied to the secondary crops during (**a**) the first experimental period (19–60 DATp; 1–42 DATs) and (**b**) the second experimental period (137–190 DATp; 1–54 DATs). T1 (0%DS + 100%FS); T2 (50%DS + 50%W); T3 (75%DS + 25%W); T4 (100%DS + 0%W).

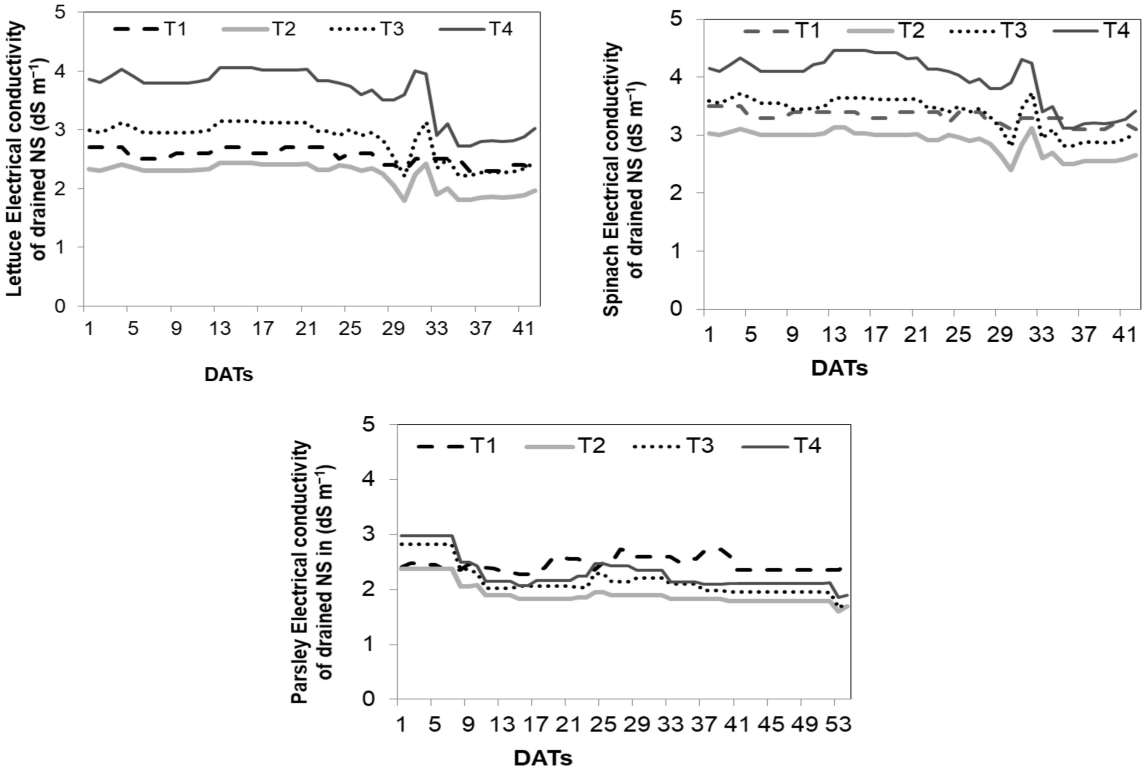


Figure 3. Evolution of EC values of the DS of the secondary crops. T1 (0%DS + 100%FS); T2 (50%DS + 50%W); T3 (75%DS + 25%W); T4 (100%DS + 0%W).

The amount of water added in each treatment affected the amount of NS was uptaken by the plants in different ways. The lettuce and parsley plants in the monoculture system absorbed at least 18% more than the plants in the cascade system receiving any of the treatments ($p < 0.05$). In spinach, the plants receiving the T3 and T4 treatments absorbed similar amounts to with the control treatment, with no significance differences among them ($p > 0.05$). Here, only the plants fertigated with 50% DS and 50% water were not able to absorb the necessary amount provided in the control treatment.

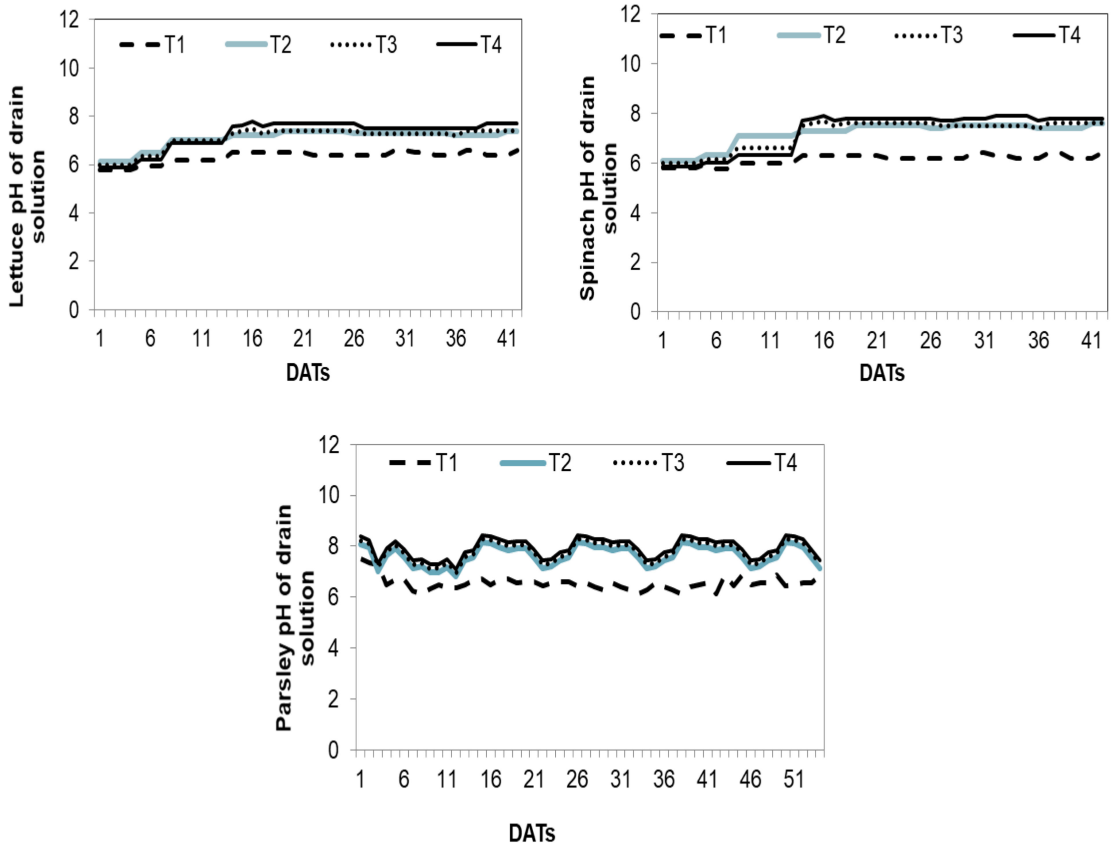


Figure 4. Evolution of pH values of the DS of the secondary crops. T1 (0%DS + 100%FS); T2 (50%DS + 50%W); T3 (75%DS + 25%W); T4 (100%DS + 0%W).

Table 2. Total amount of nutrient solution supplied to, drained from and uptaken by primary and secondary crops (L m^{-2}) for the same cultivation period, according to the treatment. The nutrient solution supplied is presented separately from the amount of water and drainage solution added.

Crop Species	Volume of NS Applied (L m^{-2})		Volume of NS Drained (L m^{-2})	Water Uptake (L m^{-2})
Tomato	882		472	410
Lettuce	Water	DS		
T1	290	0	155	135
T2	145	145	180	110
T3	215	75	195	95
T4	0	290	185	105
Spinach	Water	DS		
T1	290	0	85	205
T2	145	145	130	160
T3	215	75	95	195
T4	0	290	105	185
Parsley	Water	DS		
T1	167	0	89	105
T2	84	84	86	86
T3	124	43	109	74
T4	0	167	93	82

T1 (0%D + 100%FS); T2 (50%D + 50%W); T3 (75%D + 25%W); T4 (100%D + 0%W).

Because the plants absorbed different amounts of NS, they also drained different amounts of DS each time. The tomato and lettuce crops provided a total of 605 L m^{-2} DS. In the tomato–spinach system layout, the collected DS was 545 L m^{-2} and in the tomato–parsley system, 549 L m^{-2}. According to these data, all three cascade systems collected an amount of DS at least 48% lower than that observed in the corresponding monoculture systems. The lowest impact on the environment was considered to be exhibited by the T4 treatment, with amounts equal to 382 L m^{-2}, 313 L m^{-2}, 409 L m^{-2} for lettuce, spinach and parsley, respectively.

The above values correspond to a primary crop cultivation area equal to that of the secondary crop (1:1 cultivation ratio). Increasing the cultivation area of the secondary crop, these rates could be lower. For instance, at a higher cultivation ratio like 1:2, where the cultivation area of secondary crop is doubled, the unused DS of the primary crop was calculated to be less than 40%. In spinach, a 1:3 cultivation ratio could further reduce the amount of unused DS of the primary crop by 10%.

3.4. Nutrient Concentration

In Tables 3 and 4, the nutrient concentrations, measured in the laboratory, of the NS supplied to, uptaken by and drained from the plants in the primary and secondary crops on 36 DATs and 54 DATs, respectively, are presetned. For technical reasons, nutrient analysis was performed only for the parsley plants. As expected, the nutrient concentration of the NS supplied to the tomato and control parsley plants was similar to the system settings (Table 1). It is likely that any differences occurred due to the concentrations of nutrients remaining in the tube network.

Table 3. The average nutrient concentration in the supplied to, uptaken by and drained from the tomato and parsley plants according to treatment, on 36 DATs of the second experimental period. The concentrations of NO_3, P, K, Ca, Na, Mg are expressed in mmol L^{-1} and those of Fe, Zn, Mn, Cu in μmol L^{-1}.

Crop	Treatment	NO_3	P	K	Ca	Na	Mg	Fe	Zn	Mn	Cu	Drainage Percentage (%)
	36 DATs				Irrigation Solution							
Tomato		9.50	0.19	4.50	4.14	1.30	2.03	17.42	5.92	3.80	0.70	
Parsley	T1	11.00	0.36	6.49	4.80	1.27	1.91	15.00	2.80	2.94	0.80	
	T2	7.17	0.16	2.72	4.09	1.22	2.86	13.33	3.16	3.30	0.84	
	T3	9.53	0.24	3.96	4.29	1.26	2.98	15.37	4.73	4.60	0.97	
	T4	11.90	0.32	5.20	4.50	1.30	3.10	17.42	6.30	5.90	1.10	
	36 DATs				Drainage Solution							
Tomato		11.90	0.32	5.20	4.50	1.30	3.10	17.42	6.30	5.90	1.10	44
Parsley	T1	18.39	0.30	8.32	8.05	2.01	3.03	21.85	2.00	3.46	1.09	36
	T2	6.97	0.08	1.35	5.56	1.53	4.08	16.26	0.10	0.13	1.76	44
	T3	10.61	0.19	1.09	4.69	2.02	3.32	8.98	1.51	0.85	0.90	45
	T4	10.75	0.21	4.20	5.51	1.44	4.03	17.17	0.15	8.02	1.94	42
	36 DATs				Uptaken Solution							
Tomato		7.61	0.09	3.95	3.86	1.30	1.19	17.42	5.62	2.15	0.39	
Parsley	T1	9.77	0.35	5.46	2.97	0.85	1.28	11.15	2.30	2.64	0.50	
	T2	5.44	0.09	0.77	2.83	1.12	1.71	6.78	0.52	0.50	0.13	
	T3	7.24	0.24	3.33	2.66	1.20	2.00	11.43	3.88	4.14	0.66	
	T4	9.03	0.31	4.38	2.78	1.20	2.08	12.95	5.17	5.31	0.75	

T1 (0%DS + 100%FS); T2 (50%DS + 50%W); T3 (75%DS + 25%W); T4 (100%DS + 0%W).

Table 4. The average nutrient concentration in the supplied to, uptaken by and drained from the tomato and parsley plants, according to the treatment, on 54 DATs of the second experimental period. The concentrations of NO_3, P, K, Ca, Na, and Mg are expressed in mmol L^{-1} and those of Fe, Zn, Mn, and Cu in μmol L^{-1}.

Crop	Treatment	NO_3	P	K	Ca	Na	Mg	Fe	Zn	Mn	Cu	Drainage Percentage (%)
	54 DATs					Irrigation Solution						
Tomato		8.20	0.14	3.10	3.10	1.17	2.02	17.11	1.30	1.69	0.55	
Parsley	T1	12.41	0.26	6.36	4.60	1.27	1.79	14.68	1.10	2.77	0.60	
	T2	5.83	0.13	1.75	3.53	1.15	2.32	13.17	1.60	1.75	0.74	
	T3	7.52	0.05	0.41	4.80	0.67	2.79	24.51	0.02	2.49	1.35	
	T4	9.21	0.26	3.26	3.38	1.17	2.02	17.11	1.45	2.80	0.90	
	54 DATs					Drainage Solution						
Tomato		9.21	0.26	3.26	3.38	1.17	2.02	17.11	1.45	2.80	0.90	42
Parsley	T1	12.10	0.06	2.88	7.86	2.20	3.29	26.10	0.20	2.56	1.07	29
	T2	2.86	0.04	0.74	5.20	0.69	3.13	20.09	0.03	2.25	1.29	39
	T3	3.57	0.05	0.41	4.80	0.67	2.79	24.51	0.02	2.49	1.35	39
	T4	4.56	0.05	0.49	6.03	0.59	2.72	24.96	0.80	1.30	1.33	40
	54 DATs					Uptaken Solution						
Tomato		7.47	0.06	2.98	2.90	1.17	2.02	17.11	1.19	0.88	0.30	
Parsley	T1	9.42	0.26	5.35	2.85	0.85	1.20	10.91	0.90	2.49	0.41	
	T2	4.42	0.13	1.48	2.18	1.10	1.56	9.79	1.31	1.58	0.50	
	T3	5.71	0.19	2.11	2.14	1.08	1.46	11.26	0.90	2.05	0.56	
	T4	6.99	0.25	2.75	2.09	0.80	1.36	12.72	1.20	2.52	0.61	

T1 (0%DS + 100%FS); T2 (50%DS + 50%W); T3 (75%DS + 25%W); T4 (100%DS + 0%W).

The nutrient concentrations were similar between the DS for the primary crop and the NS supplied to the plants receiving the T4 treatment, at both the 36 and 54 DATs sampling dates. On the other hand, the nutrients supplied to the cascade treatments were different from the target concentration, and varied according to the sampling date. On 36 DATs, most of the macronutrient concentrations of T4 were similar to the targeted concentration applied to the plant of the control treatment (Table 3). Significant differences were observed with respect to micronutrient concentration, with higher values in the DS applied to the primary crop ($p < 0.05$). The macronutrient concentrations of the other treatments—T2 and T3—were between 13% and 59% lower than in the control treatment ($p < 0.05$), and the micronutrient concentrations were between 21% and 69% higher than in the control treatment ($p < 0.05$).

On 54 DATs, the nutrients in the DS primary crop were lower than those collected on 36 DATs, affecting the synthesis of NS supplied to the cascade treatments (Table 4). Therefore, none of the cascade treatments were able to be irrigated with nutrient concentrations close to those targeted. In the T4 treatment, most of the element contents were 25–49% lower than the target.

The synthesis of the NS supplied to the plants affected the amount of NS absorbed by the secondary crops and the resulting synthesis of the DS in different ways. On 36 DATs, the plants receiving T1, T3 and T4 absorbed between 11% and 38% of the nutrients of the supplied NS. In contrast, for the T2 treatment, where the NS supplied was poor, the plants absorbed the majority of the nutrients. On 54 DATs, no significant differences were observed among the treatments ($p < 0.05$).

All the cascade treatments presented lower nutrient concentrations in the DS compared to the control treatment. The DS with the lowest concentrations of NO_3, P, Zn and Mn was that used in the T2 treatment. The contents of most of the elements in that treatment were 24–96% lower (depending on the element) than in the control plants. The T3 treatment presented the lowest concentrations of K, Ca, Mg, Fe, and Cu. The differences between the cascade treatments and the control treatment were similar on both sampling dates. However, on the second sampling date (54 DATs), the contents of most of the macronutrients, except Ca, in the final DS were 25–65% lower than on the first sampling date.

Table 5 presents the nutrient content (N, P, K, Ca and Mg expressed in g per 100 g DM, and microelements Fe, Zn, Mn, Cu expressed in mg kg^{-1} DM) in the leaf tissues of lettuce, spinach and parsley plants subjected to the different treatments on the different sampling dates. In lettuce leaves, the lowest concentrations of most of the macronutrients were found for the T4 treatment. In the other treatments, no significant differences were observed. In spinach leaves, the highest concentrations of N, P and K were observed in T1, while Ca and Mg were higher with the T4 treatment. In parsley plants, the concentration of most of the nutrients was lower in the cascade than in the control treatment.

Table 5. Nutrient content (N, P, K, Ca and Mg expressed in g per 100 g DM, and microelements Fe, Zn, Mn, Cu expressed in mg kg^{-1} DM) in leaf tissues of lettuce, spinach and parsley plants of the different treatments and sampling dates (*n* = 9).

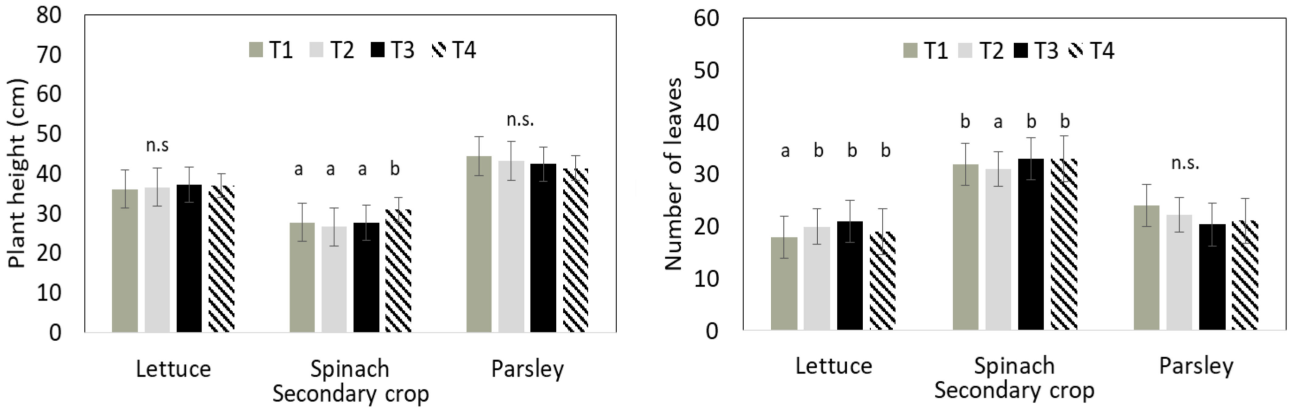
Crop	Treatment	N	P	K	Ca	Mg	Fe	Zn	Mn	Cu
Lettuce										
15 DATs	T1	4.15 ^{aA,1}	0.67 ^{aA}	7.06 ^{aA}	1.03 ^{aA}	0.49 ^{aA}	148.7 ^{aA}	31.7 ^{aA}	26.8 ^{aA}	5.89 ^{aA}
	T2	4.11 ^{aA}	0.67 ^{aA}	8.18 ^{bA}	1.00 ^{aA}	0.39 ^{bA}	233.47 ^{bA}	40.1 ^{bA}	33.9 ^{bA}	4.82 ^{aA}
	T3	4.01 ^{aA}	0.60 ^{bA}	7.14 ^{aA}	1.06 ^{aA}	0.54 ^{cA}	141.4 ^{aA}	29.8 ^{aA}	26.8 ^{aA}	4.33 ^{aA}
	T4	3.61 ^{aA}	0.55 ^{cA}	6.67 ^{aA}	0.92 ^{aA}	0.45 ^{aA}	156.8 ^{aA}	28.6 ^{aA}	28.7 ^{aA}	4.99 ^{aA}
41 DATs	T1	3.54 ^{aA}	0.64 ^{aA}	6.03 ^{aA}	1.29 ^{aB}	0.65 ^{aB}	122.5 ^{aA}	28.5 ^{aA}	26.8 ^{aA}	7.01 ^{aA}
	T2	3.62 ^{aA}	0.58 ^{aB}	5.25 ^{abB}	1.26 ^{aB}	0.63 ^{aB}	160.5 ^{bB}	37.2 ^{bA}	36.4 ^{aA}	4.11 ^{aA}
	T3	3.38 ^{aA}	0.49 ^{bB}	4.78 ^{abB}	1.28 ^{aB}	0.69 ^{aB}	126.2 ^{aA}	28.9 ^{aA}	33.4 ^{aB}	4.08 ^{aA}
	T4	3.30 ^{aA}	0.44 ^{bB}	4.56 ^{bB}	1.23 ^{aB}	0.66 ^{aB}	119.7 ^{aA}	27.5 ^{aA}	31.9 ^{aA}	3.86 ^{aA}
	Optimal levels	4.32	0.89	4.91	0.76	0.65	82.8	24.8	39.7	4.84
Spinach										
15 DATs	T1	4.17 ^{aA}	0.71 ^{aA}	6.78 ^{aA}	1.47 ^{aA}	1.10 ^{aA}	69.42 ^{aA}	31.9 ^{aA}	18.6 ^{aA}	3.33 ^{aA}
	T2	4.28 ^{aA}	0.74 ^{aA}	8.48 ^{bA}	1.13 ^{bA}	1.29 ^{bA}	83.75 ^{bA}	44.9 ^{bA}	26.8 ^{bA}	4.94 ^{bA}
	T3	4.22 ^{aA}	0.59 ^{bA}	6.69 ^{aA}	1.34 ^{cA}	1.23 ^{bA}	66.88 ^{aA}	31.0 ^{aA}	18.1 ^{aA}	3.56 ^{aA}
	T4	4.25 ^{aA}	0.58 ^{bA}	6.90 ^{aA}	1.34 ^{aA}	1.23 ^{bA}	66.96 ^{aA}	31.4 ^{aA}	19.8 ^{aA}	3.10 ^{aA}
41 DATs	T1	4.54 ^{aA}	0.67 ^{aA}	7.80 ^{aA}	1.85 ^{aB}	1.37 ^{aB}	85.34 ^{aB}	38.6 ^{aB}	26.7 ^{aB}	3.74 ^{aA}
	T2	4.37 ^{aA}	0.62 ^{aB}	6.62 ^{bB}	1.63 ^{bB}	1.50 ^{bB}	86.55 ^{aB}	51.45 ^{bB}	28.6 ^{aA}	5.38 ^{bA}
	T3	4.25 ^{aA}	0.50 ^{bA}	5.51 ^{cB}	2.07 ^{aB}	1.60 ^{bB}	90.26 ^{aB}	38.5 ^{aB}	24.7 ^{aB}	5.32 ^{bB}
	T4	4.21 ^{aA}	0.51 ^{bA}	6.17 ^{bA}	1.93 ^{aB}	1.57 ^{bB}	85.54 ^{aB}	38.9 ^{aB}	25.3 ^{aB}	4.76 ^{bB}
	Optimal levels	4.61	0.60	5.27	1.40	1.00	60.35		unspecified	
Parsley										
36 DATs	T1	3.78 ^{aA}	0.84 ^{aA}	6.00 ^{aA}	0.97 ^{aA}	0.27 ^{aA}	105.7 ^{aA}	25.9 ^{aA}	35.4 ^{aA}	5.83 ^{aA}
	T2	3.99 ^{aA}	0.42 ^{bA}	2.48 ^{bA}	1.27 ^{bA}	0.60 ^{bA}	87.3 ^{bA}	32.6 ^{aA}	48.4 ^{bA}	8.19 ^{aA}
	T3	3.57 ^{aA}	0.34 ^{bA}	2.16 ^{cA}	1.17 ^{bA}	0.63 ^{bA}	108.7 ^{aA}	29.5 ^{aA}	43.9 ^{bA}	7.82 ^{aA}
	T4	3.69 ^{aA}	0.39 ^{bA}	2.68 ^{bA}	1.23 ^{bA}	0.64 ^{bA}	81.39 ^{bA}	24.6 ^{aA}	45.7 ^{bA}	7.16 ^{aA}
54 DATs	T1	3.43 ^{aA}	0.62 ^{aB}	5.63 ^{aA}	1.09 ^{aA}	0.28 ^{aA}	76.33 ^{aB}	19.6 ^{aA}	28.8 ^{aB}	4.53 ^{aB}
	T2	2.97 ^{aB}	0.24 ^{bB}	1.12 ^{bB}	1.32 ^{bA}	0.80 ^{bB}	64.61 ^{bB}	20.4 ^{aB}	35.7 ^{aB}	5.56 ^{aB}
	T3	3.17 ^{aA}	0.27 ^{bB}	1.46 ^{cB}	1.29 ^{bA}	0.71 ^{bB}	71.91 ^{aB}	21.0 ^{aB}	30.8 ^{aB}	4.4 ^{aB}
	T4	3.02 ^{aB}	0.23 ^{bB}	1.19 ^{bB}	1.33 ^{bA}	0.73 ^{bB}	69.87 ^{aB}	19.2 ^{aA}	34.6 ^{aB}	5.3 ^{aB}
	Optimal levels	4.7	0.72	5.8	0.84	0.40	75	57	107	10

[1] Different uppercase letters (A, B) indicate statistically significant differences between sampling dates and different lowercase letters (a, b) indicate statistically significant differences between the different (T1–T4) treatments ($p < 0.05$). T1 (0%DS + 100%FS); T2 (50%DS + 50%W); T3 (75%DS + 25%W); T4 (100%DS + 0%W). The optimal level was defined by El-Shinawy and Gawish [23] for lettuce, Öztekin et al. [24] for spinach, and Currey et al. [25] for parsley.

3.5. Yield Performance of Secondary Crops

To assess the sustainability of each cascade system, it is necessary to study the yield performance of the secondary crops. In this sense, a series of yield characteristics including plants height, number of leaves, chlorophyll content index, photosynthesis rate, FM and DM were analysed. The data presented here correspond to the last day of each secondary crop cultivation period (42 DATs for lettuce and spinach; 54 DATs for parsley). The measurements collected in the earlier pre-harvest cultivation period are not considered, since no significant differences among the treatments were noticed.

Figure 5a presents the average plant height of each secondary crop, according to the treatment, measured during the last day of each cultivation period. According to the results, the nutrient solution applied to the lettuce and parsley did not affect the height ($p > 0.05$) of the plants. Spinach plants showed a final plant height 14% higher for the T4 treatment ($p < 0.05$) compared to the rest of the treatments.



(**a**) (**b**)

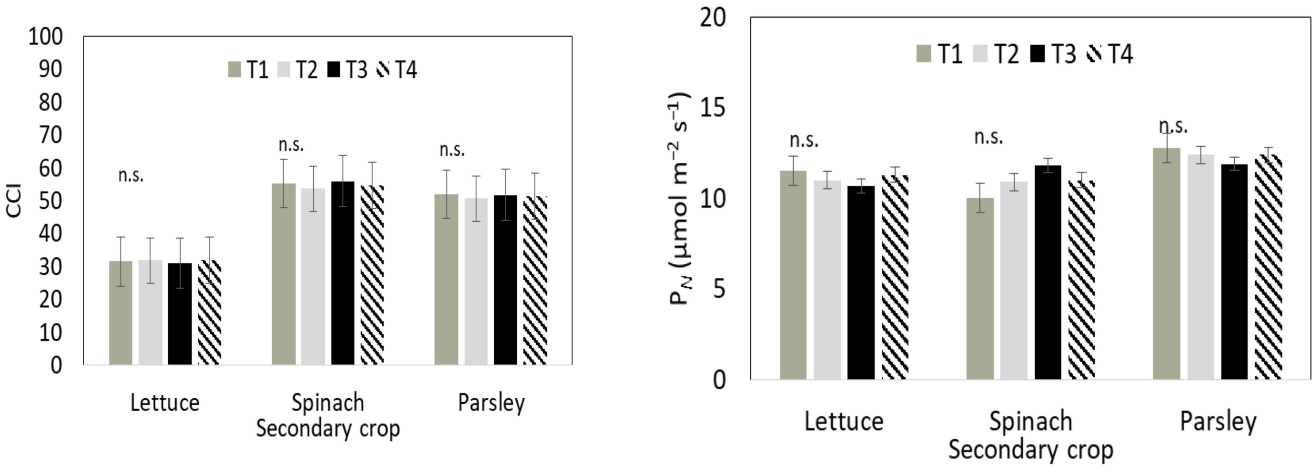
Figure 5. Mean values and standard deviations of (**a**) plant height (cm), and (**b**) number of leaves measured on the last day of each secondary cultivation period grown under the different treatments ($n = 9$ samples/treatment). T1 (0%DS + 100%FS); T2 (50%DS + 50%W); T3 (75%DS + 25%W); T4 (100%DS + 0%W). Different lowercase letters (a, b) indicate statistically significant differences ($p < 0.05$) of the different treatments within each crop, n.s. indicates no significant difference ($p > 0.05$).

The number of leaves per plant for the different treatments during the last day of each secondary crop cultivation period is presented in Figure 5b. Lettuce plants fertigated with the targeted NS (T1 treatment) had significantly lower numbers of leaves compared to the other treatments. Spinach plants with the T2 treatment presented significantly lower numbers of leaves compared to the other treatments. No treatment effect was in the number of leaves of parsley plants ($p > 0.05$).

Figure 6 presents the variation in CCI for each secondary crop according to the treatment measured during the last day of the cultivation period of each secondary crop. The average values of chlorophyll content observed during the measurement period were 32 mg cm^{-2}, 55 mg cm^{-2}, and 45 mg cm^{-2} for lettuce, spinach, and parsley, respectively. No treatment effects were observed on the CCI ($p > 0.05$).

Figure 7 presents the P_N variation of each secondary crop according to the treatment during the last day of the cultivation period of each secondary crop. The average P_N values observed in the different secondary crops were 12 µmol CO_2 m^{-2} s^{-1} for lettuce and spinach and 10 µmol CO_2 m^{-2} s^{-1} for the parsley crop. Similar to CCI, no treatment effects were observed on P_N ($p > 0.05$).

The values of FM and DM production observed in the different treatments are shown in Table 6. In the lettuce crop, no significant difference was observed among the treatments ($p > 0.05$). The moisture content of the samples ranged from 93% to 95%. In the spinach crop, only the FM with the T2 treatment was less than the FM of the control treatment, by about 22% ($p < 0.05$). The moisture content of the samples ranged from 88 to 90%. Parsley presented the highest yield in the control treatment and the reuse of the tomato drainage solution imposed a decrease in yield by about 30%. The moisture content of the parsley samples was 83%.



(**a**) (**b**)

Figure 6. Mean values and standard deviations of (**a**) CCI and (**b**) P_N (μmol CO_2 m^{-2} s^{-1}), measured on the last day of each secondary cultivation period under the different treatments (n = 9 samples/treatment). T1 (0%DS + 100%FS); T2 (50%DS + 50%W); T3 (75%DS + 25%W); T4 (100%DS + 0%W). n.s. indicates no significant difference ($p > 0.05$).

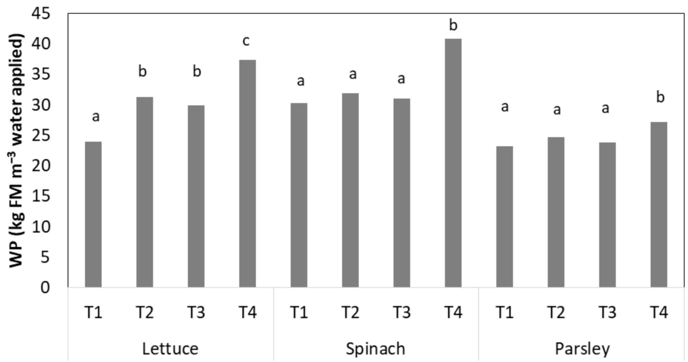


Figure 7. Water productivity in kg of fresh mass per kg of water applied based on the systems layout in combination with the primary crop for a six-month cultivation period. Different lowercase letters (a, b, c) within each secondary crop indicate statistically significant differences ($p < 0.05$).

Table 6. Mean value (and standard deviation) of fresh mass (FM) and dry mass (DM) in g m^{-2} of the secondary crops on the two sampling dates.

Crops	Lettuce		Spinach		Parsley	
	FM (g m^{-2})	DM (g m^{-2})	FM (g m^{-2})	DM (g m^{-2})	FM (g m^{-2})	DM (g m^{-2})
DAT	28		28		36	
T1	$966 \pm 11^{a,1}$	42 ± 0.8^{a}	1300 ± 37.7^{a}	128 ± 3.8^{a}	67 ± 10.7^{b}	11 ± 1.7^{b}
T2	1011 ± 8.8^{b}	46 ± 1.0^{b}	1192 ± 24.9^{a}	120 ± 2.5^{a}	56 ± 9.2^{ab}	11 ± 1.7^{b}
T3	1134 ± 9.1^{b}	47 ± 1.0^{b}	1392 ± 36.4^{ab}	140 ± 3.6^{ab}	48 ± 7.2^{a}	10 ± 1.2^{a}
T4	1045 ± 9.4^{b}	47 ± 0.8^{b}	1548 ± 58.8^{b}	156 ± 5.9^{b}	45 ± 4.7^{a}	8 ± 0.8^{a}
DAT	42		42		54	

Table 6. *Cont.*

Crops	Lettuce		Spinach		Parsley	
	FM (g m^{-2})	DM (g m^{-2})	FM (g m^{-2})	DM (g m^{-2})	FM (g m^{-2})	DM (g m^{-2})
T1	2354 ± 39.3 ^{a}	98 ± 2.8 ^{b}	2904 ± 45.3 ^{b}	292 ± 4.5 ^{b}	329 ± 33.6 ^{b}	46 ± 8.6 ^{b}
T2	2117 ± 33.9 ^{a}	90 ± 2.9 ^{a}	2272 ± 67.5 ^{a}	216 ± 5.5 ^{a}	207 ± 21.9 ^{a}	32 ± 3.4 ^{a}
T3	2276 ± 19.1 ^{a}	94 ± 2.0 ^{ab}	2576 ± 26.2 ^{ab}	260 ± 5.6 ^{ab}	229 ± 18.6 ^{a}	37 ± 3.1 ^{a}
T4	2318 ± 47.4 ^{a}	100 ± 2.7 ^{b}	3040 ± 82.0 ^{b}	284 ± 5.3 ^{b}	226 ± 27.8 ^{a}	35 ± 4.2 ^{a}

[1] Different lowercase letters (a, b) within a row for FM or for DM indicate statistically significant differences ($p < 0.05$).

3.6. Water Productivity and Fertiliser Use Efficiency

Figure 7 presents the WP (kg FM m^{-3} water applied) of each cultivation system. To ensure comparability of data among the systems, the calculations were performed for a growing period equal to that of the primary crop. The WP value estimated for the tomato crop was 26.5 kg m^{-3}. The WP values of the secondary crops with the control treatment were equal to 24 kg m^{-3}, 30 kg m^{-3} and 23 kg m^{-3} for lettuce, spinach and parsley, respectively. In the cascade system with T4, the WP values were significantly higher than in the monoculture system, by 50%, 30% and 14% for lettuce, spinach and parsley, respectively. In the cascade systems with other treatments, the WP values of parsley and spinach were equal to that of the monoculture system ($p > 0.05$), while in the lettuce crop, WP was slightly higher ($p < 0.05$).

The FUE (kg FM kg^{-1} fertiliser applied) of tomato during the six-month cultivation period was 20.9 kg FM kg^{-1} fertiliser applied. For the same cultivation period, the FUE was calculated to be equal to 18 kg FM kg^{-1} for lettuce, 20 kg FM kg^{-1} for spinach and 17 kg FM kg^{-1} for parsley. In the cascade system where only DS was used, the FUE was significantly higher than in the monoculture system (T1), by 62% for lettuce and spinach and 22% for parsley. The FUE values of the other cascade treatments were also higher than in the monoculture system. The NUE and PUE showed similar trends (Figure 8). The NUE varied from 42 kg FM kg^{-1} to 74 kg FM kg^{-1}, with the maximum values being found for the T4 treatment. The PUE values were significantly higher than those of NUE, since the amount of P added to the irrigated NS was quite low, almost 90% less than the N concentration. Therefore, PUE varied from 463 kg FM kg^{-1} to 1270 kg FM kg^{-1}, with the maximum values being observed for the T4 treatment. The other cascade treatments resulted in NUE and PUE values close to those of the monoculture system.

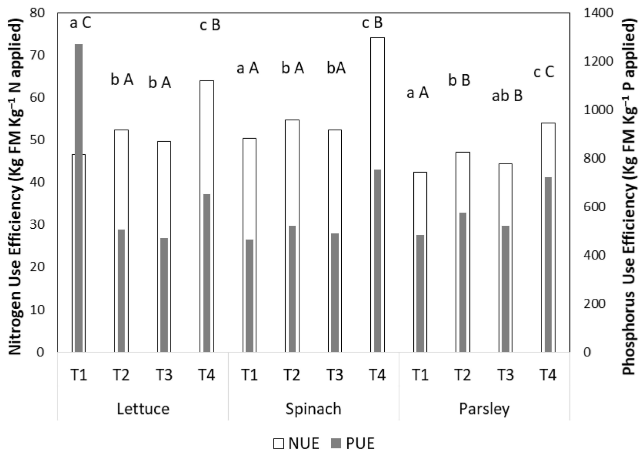


Figure 8. Nitrogen and phosphorus use efficiency in kg of fresh mass per kg of nutrient applied based on the system layout in combination with the primary crop for six-month cultivation period. Different lowercase letters (a, b, c) indicate statistically significant differences ($p < 0.05$) in NUE and uppercase letters (A, B, C) indicate statistically significant differences ($p < 0.05$) in PUE.

4. Discussion

The correct choice of crop combinations and system layouts is the key to the efficient functioning of cascade systems. In the current research, three different cascade systems with three different crop species were compared with the respective monoculture system.

Among the cascade systems, the NS that used pure Ds of the primary crop had a macronutrient concentration closer to the targeted concentration. The micronutrients, on the other hand, were closer to the targeted concentration in the cascade systems where the DS was diluted with water. In the case of Fe concentrations, although the values were much higher at both sampling dates for recycling treatments than when operating as an open system, they were still clearly above critical levels, as suggested by [26,27]. These results were confirmed by the nutrient concentration estimated in leaf tissues.

Spinach and parsley seem to be more adjustable than the lettuce crop in secondary crop cultivation systems, since they are more salt tolerant. Usually, lettuce is considered to be more moderately sensitive to salinity compared to spinach and parley crops, with a threshold electrical conductivity (EC) of 1.3 dS m^{-1}, and a negative relative yield decrease slope of 13%. The respective values for spinach and parsley were 2.0 dS m^{-1} with a slope of 7.6% per dS m^{-1} and 1.8 dS m^{-1} with a slope of 6.2% per dS m^{-1} [28].

However, in this study, all crops were able to grow sufficiently under the cascade system, although the amounts of nutrients absorbed were different. The CCI and P_N values of all crops were similar in all cultivation systems. The lettuce plants in the cascade systems were sufficiently tall and heavy, with a greater number of leaves than in the monoculture system. The spinach plants subjected to the T4 cascade treatment were taller and heavier than those in the other systems, while the parsley plants demonstrated similar growth progress to that of the monoculture system, but were less heavy. It seems that all of the studied crops could be used as secondary crops in cascade cultivation systems, given that they exhibit sufficient yield performance. The final evaluation of cascade systems, however, should be undertaken in consideration of water productivity and nutrient use efficiency.

4.1. Evaluation of Cascade System Based on Water Productivity

In the primary crop, the WP values observed (26.5 kg FM m^{-3}) were similar to those reported in [6]. In Katsoulas et al. [1], the WP of tomato crop varied from 20 kg FM m^{-3} to 35 kg FM m^{-3}. Nikolaou et al. [29] mentioned that the ratio of product yield to water use increased from 3 kg m^{-3} to 17 kg m^{-3} in an unheated greenhouse and reached 45 kg m^{-3} in a soilless growing system.

In secondary crops, the WP values for the monoculture system were 25 kg m^{-3}, 31 kg m^{-3} and 24 kg m^{-3} for lettuce, spinach and parsley, respectively. Bozkurt et al. [30] found an FM of 23 kg m^{-3} for lettuce plants cultivated in soil under greenhouse conditions. Here, the lettuce plants with T4 exhibited a WP performance 50% than that of the monoculture system. Moreover, the plants in the cascade system subjected to T2 and T3 also had a WP performance 26% higher than in the monoculture system.

Kuslu et al. [31] found a WP of 9.7 kg m^{-3} in spinach crops after a cultivation period of about 45 days. Here, for the same cultivation period, the WP of the monoculture system exhibited similar values. During the primary crop cultivation period of six months, the WP was almost tripled. In the cascade system with T4, the WP was even higher, with an increase of about 30% with respect to the monoculture system.

In parsley plants, Martins et al. [32] found WP values ranging from 3.7 kg m^{-3} to 4.73 kg m^{-3} under greenhouse conditions with a coconut substrate. Here, for the same cultivation period, the WP was 34% higher. During the primary crop cultivation period of six months, WP was about 24 kg m^{-3} in the monoculture system. In the cascade system with T4, the WP was 14% higher than that of the monoculture system.

Accordingly, the two-level cascade cultivation system was demonstrated to be most efficient from an agronomical point of view, since the net water input was restricted, and the WP was significantly higher than in the open system. Understanding and further improving WP under cascade system side yield is the primary focus of developing water productive plants in greenhouses. The improvement in WP could impart tolerance to drought and salinity stress, while still accumulating sufficient biomass to make their production commercially viable. According to Damerum et al. [33], it is imperative to develop systems for improving crop WP, particularly in the case of crops such as lettuce, where over 75% of the total production in the US is dominated by the state of California. The combination of DS with fresh nutrient solution may allow this goal to be achieved, and should be further investigated.

4.2. Evaluation of Cascade System Based on Nutrient Use Efficiency

Compared to open (free drainage) soilless systems, cascade systems can be considered that has higher fertiliser use efficiency, since they make complete use of the drainage produced from the primary (and potentially the secondary) crop.

In the current research, the FUE values of the cascade parsley and lettuce systems (18 kg FM kg^{-1}) were 18% and 62% higher than in the monoculture (control) treatment. The FUE values of the lettuce monoculture system were similar to the values found by Santamaria et al. [34] in lettuce plants cultivated in soilless growth chambers.

In the spinach crop, the FUE value was 0.20 kg FM kg^{-1} for the 42-day cultivation period. Chan-Navarrete et al. [35] reported FUE values ranging from 0.14 kg DM kg^{-1} to 0.18 kg DM kg^{-1} for a 28-day cultivation period. For a six-month cultivation period, the FUE, expressed in FM, was calculated to be equal to 15 kg FM kg^{-1}. The FUE of the T4 treatment was 66% higher than in the monoculture system. For spinach to maintain a satisfactory yield under low nitrogen conditions, high NUE is necessary. This is because spinach is not very efficient at either nitrogen uptake or utilisation, and requires considerable amounts of nitrogen for growth and the establishment of its dark green colour [36,37]. The combination of high nitrate input and low nitrate reduction by spinach leads to high levels of nitrate in the marketable product [35]. In cascade systems, spinach plants can accumulate substantial amounts of nitrate in the leaves, because the extra mineralisation of DS gives a surplus of nitrate to the plant.

Here, the maximum NUE value occurred in cascade with the 100% DS treatment. The NUE in that system was higher than those reported in a currently available commercial hydroponic system. Zhang et al. [38] found that NUE values varied from 44 kg FM kg^{-1} to 74 kg FM kg^{-1} for a 5-month cultivation period in a microalgae and crop co-cultivation system. Similar to the present study, lower NUE values were found in the simple hydroponic system, while the maximum values were found in the co-cultivated system. The PUE values were also higher than those found for a commercial soilless system. The PUE values were more than double those reported by Zhang et al. [38], however, due to low values of P concentration added to the system. Usually, PUE is a complex trait for plant breeding, with many potential interactions and trade-offs with other factors affecting crop yield, such as water use efficiency and energy balance [39]. The effectiveness of cascade approaches in cascade systems based on traits that affect P absorption rates is due to the deeper layer of water productivity occurring.

Our results are in agreement with previous reports by Elvanidi et al. [12] and Muñoz et al. [40], which mentioned that the nitrogen balance in cascade systems shows an important decrease in nutrient leachate. According to Muñoz et al. [40], the adoption of a cascade crop system reduced the environmental impact by 21%. Additionally, García-Caparrós et al. [10] concluded that the establishment of sequential irrigation systems can result in water savings and the removal of nitrates, which are of great advantage in arid and semi-arid regions.

Cascade farming systems represent a promising sustainable alternative cultivation system compared to monoculture systems. Likewise, due to climate change and the increasing population, it is becoming a challenge to balance demand and supply, leading to negative economic externalities. However, cultivation in cascade systems, especially in hydroponic ones, can provide valuable ecosystem services, such as savings in terms of fertilisers, the consumption of less water, the minimisation of energy needs and the maximisation of yield productivity. A well-developed soilless cascade system represents a substantial competitive advantage in overcoming the challenges outlined.

However, to further assess the sustainability of cascade systems, the use of a life cycle assessment (LCA) systems analysis methodology is required for the assessment of their environmental impacts.

5. Conclusions

Three secondary crops were tested under different treatments in a soilless cascade system using a tomato crop as the primary donor crop. It was found that among the secondary crops, spinach was the most appropriate secondary receiver crop among those considered in this study. The use of the tomato drainage solution for the fertigation of the spinach crop positively affected crop yield. In the case of the other secondary crop species tested, lettuce and parsley, yield was not negatively affected when fertigated by the tomato crop drainage solution. The reuse of the drainage solution significantly increased the water productivity and nutrient use efficiency of the cascade crops. The water productivity in the plants irrigated with pure drainage solution was 50%, 30% and 14% higher for lettuce, spinach and parsley, respectively, than in the monoculture system. The nitrogen and phosphorus use efficiency were improved more than 50% with respect to their values in the monoculture system. The current research gives small holder farmers the ability to convert their cultivations to more sustainable systems, minimising construction costs and environmental impact while maximising yield.

Author Contributions: Conceptualisation, N.K.; methodology, A.E. and N.K.; formal analysis, E.K., S.F., I.N. and A.E.; investigation, E.K., A.E., S.F., I.N. and N.K.; resources, N.K.; data curation, E.K., S.F., I.N. and A.E.; writing—original draft preparation, E.K., A.E. and N.K.; writing—review and editing, A.E. and N.K.; supervision, N.K.; project administration, N.K.; funding acquisition, N.K. All authors have read and agreed to the published version of the manuscript.

Funding: The work was carried out in the frame of the CasH project, which is co-financed by the European Union and Greek national funds through the bilateral Greece–Germany S & T Cooperation Program, Competitiveness, Entrepreneurship & Innovation (EPANEK) (project code: T2DGE-0893).

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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