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Comparison of Methods to Determine Nutrient Uptake of Tomato Grown in Free-Draining Perlite Substrate—Key Information for Optimal Fertigation Management

Juan M. Cedeño [1], Juan-José Magán [2], Rodney Bruce Thompson [1,3,*], María-Dolores Fernández [2] and Marisa Gallardo [1,3,*]

[1] Department of Agronomy, University of Almeria, Carretera de Sacramento s/n, La Cañada de San Urbano, 04120 Almería, Spain; juancedeno87@gmail.com
[2] Research Station of the Cajamar, Paraje Las Palmerillas 25, 04710 El Ejido, Spain; juanjosemagan@fundacioncajamar.com (J.-J.M.); mdoloresfernandez@fundacioncajamar.com (M.-D.F.)
[3] CIAIMBITAL Research Centre for Mediterranean Intensive Geosystems and Agrifood Biotechnology, University of Almeria, La Cañada de San Urbano, 04120 Almería, Spain
* Correspondence: rodney@ual.es (R.B.T.); mgallard@ual.es (M.G.)

Abstract: Two methods were compared to determine crop nutrient uptake by tomato crops in free-draining perlite substrate. They were the nutrient balance method (applied minus drained) and the dry matter method (DM) (nutrients in plant material). Uptake of N, P, K, Ca, Mg, and S was determined using both methods, in three consecutive tomato crops planted in the same perlite. Nutrient uptake determined using the balance method was consistently higher than with the DM method. Relative differences (balance minus dry matter, with respect to the DM method) were N: −1 to 16%, P: 27–45%, K: 14–46%, Ca: 17–87%, Mg: 28–111%, and S: 15–65%. There was a clear tendency for the difference between the methods to reduce with successive crops. The differences between the methods were reduced when the measured retention of nutrients in the perlite substrate and estimated nutrient retention in roots (using a model) were included. However, these data did not explain all of the observed differences between the two methods. Various retention and loss processes may explain the differences. The results suggest that the DM matter method estimates nutrient uptake by the crop, and the balance method estimates nutrient consumption by the cropping system.

Keywords: soilless cropping; nutrient management; nutrient uptake; nutrient retention; nutrient loss; nutrient balance

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1. Introduction

There are at least 170,000 ha of plastic greenhouses used for vegetable production, in the Mediterranean Basin [1]. Approximately 80,000 ha are located in Spain, Italy and Greece [2]. In those three countries, 7–9% of greenhouses use substrate as the cropping media [2]. Of these, approximately 90% are free-draining, in that there is no collection and recirculation, and the drainage enters directly into the underlying soil [2,3]. In Poland, there are approximately 5400 ha of greenhouses using substrate, of which 95% are free-draining [2]. Therefore, there are at least 10,000 ha of greenhouses with free-draining substrate in the European Union. In Türkiye, there are 50,000 ha of greenhouses, of which 18,000 ha are in substrate (Dr. C. Karaca Akdeniz University, Antalya, Türkiye; Personal communication). Assuming that 90% are free-draining, as in southern Europe [2], there are an estimated 16,000 ha of free-draining substrate-grown crops in Turkey. Given the rapid expansion of plastic greenhouses in North Africa, Asia, and Central America [4–6], it is likely that internationally there is an appreciable additional area of greenhouses with free-draining substrate.

Free-draining substrate cultivation is associated with substantial losses of nutrients in drainage to underlying soil and aquifers [7–10]. In these cropping systems, complete

nutrient solutions are applied throughout the crop [3,11]. In commercial production in free-draining substrate, leaching fractions are commonly 30–40% of applied water [3,12].The relative loss of nutrients in drainage from free-draining substrate crops is appreciably more than from soil-grown greenhouse crops, per unit area [9,10]. Contributing factors are the requirement for a drainage fraction to prevent salinity accumulation and the limited retention of nutrients in the relatively inert substrate materials [3,12].

The nutrient losses from greenhouse vegetable production are associated with appreciable environmental contamination of water bodies [13–16]. Considerable and increasing legislative and consumer pressures are being applied to reduce these nutrient losses and the associated contamination [17,18]. To reduce the environmental impact caused by drainage of nutrients from free-draining substrate-grown vegetable crops, various tools are available to assist with the optimization of irrigation management, such as soil moisture sensors, drainage trays, computer tools to estimate irrigation requirements, etc. [2,3,19–22]. However, to reduce the large nutrient loss, optimal fertigation management requires that the management of both irrigation and nutrients be optimized [11,23–25].

An established approach for nutrient management of substrate-grown crops is crop uptake concentration [23,26–28] Uptake concentration is the crop uptake of a nutrient divided by crop water use (i.e., crop evapotranspiration, etc.) for the same time period [23,29]. It has no physiological basis; however, it is considered to be a very effective tool for practical nutrient management [23,26–28]. Maintaining the applied nutrient concentration slightly lower than the uptake concentration can appreciably reduce nutrient losses in drainage while maintaining production [9,30] Nutrient uptake concentrations can be estimated using model-based Decision Support Systems (DSS) that estimate crop nutrient uptake and ETc [31,32]. These DSS estimations can be based on long-term average climate data or forecast climatic data [32]. Data of crop nutrient uptake are also useful for estimating crop nutrient requirements in semi-closed and closed systems [31,33,34]. Because of their importance for nutrient management in substrate growing systems, accurate data of crop nutrient uptake are essential.

Two approaches are used to measure the crop uptake of nutrients of substrate-grown crops, both for calculation of uptake concentration and for estimating crop nutrient requirements. The first approach is the nutrient balance method, in which the difference between the amount applied and the amount drained is calculated. It is assumed that the difference between the amounts applied and drained is the amount taken up by the crop. This approach requires frequent analyses of applied nutrient and drainage solutions. With availability of appropriate laboratory analytical capacity, it provides rapid results without a large labor requirement. The second approach is the dry matter method, in which the amounts of nutrients in above-ground plant material are determined at intervals throughout the crop. This is a more laborious and slower method that requires appreciable processing of plant material and laboratory analysis.

The balance approach assumes that the difference between the amounts applied and drained will be the same as that measured in the crop by the dry matter method. However, differences have been reported between the two methods. Higher values of nutrient uptake for various nutrients were obtained using the balance method compared to the dry matter method for tomato grown in rockwool [35]. In a study with young tomato plants grown with a Nutrient Film Technique (NFT), a substrate-free hydroponic system, the measured nutrient uptake was higher when using the balance method compared to the dry matter method [36]. Currently, there is no clear understanding as to whether there definitely are differences between estimates of nutrient uptake using these two methods with particular substrates. If such differences exist, they could result in inaccurate estimations of crop nutrient uptake. If there are differences between the two methods, the size of the effects should be quantified, and changes with time characterized. It is also essential to understand the differences in order know which method is the most appropriate for a given application.

The objectives of the present study were to determine crop uptake of N, P, K, Ca, Mg, and S using the dry matter method and the nutrient balance method for tomato grown in

free-draining perlite, and to compare values of the two methods over a sequence of three successive tomato crops, all grown in the same substrate.

2. Materials and Methods

2.1. Location and Crop Details

Three successive tomato crops (*Solanum lycopersicum* L.) were grown in a plastic greenhouse at the Research Station of the Cajamar Foundation in Almeria, SE Spain (2°43′ W; 36°48′ N; 155 m.a.s.l.). The greenhouse had a multi-span design, with a polyethylene cover and passive ventilation. Its total area was 960 m^2 (40 m × 24 m), of which 840 m^2 was used for cropping. The crops grown in the greenhouse were an Autumn crop, from 9 September 2020 to 1 February 2021 (145 days); a Spring crop, from 17 January 2020 to 30 June 2021 (133 days); and a Long Cycle crop from 14 September 2021 to 17 May 2022 (245 days). The tomato cultivar used for all three crops was Realsol (Rijk Zwaan, De Lier, The Netherlands), which was grafted onto cv. King Kong RZ (Rijk Zwaan) for the Spring crop, and cv. Multiflor (Bayer, Leverkusen, Germany) for the Long Cycle crop. The Autumn crop was not grafted. Crop management and conditions were very similar to those in commercial greenhouses in the region.

The plants were grown in 37 L bags of perlite, with a particle size diameter of 0–6 mm. The bags of perlite were new for the Autumn crop; the same bags were used for the two subsequent crops. There was no collection and re-circulation of drainage water. The bags were slit open at the bottom to allow free drainage to the underlying soil. There were three plants per bag. The perlite bags were organized in paired rows, with 0.5 m between plants and between bags in the same paired row, and 2 m between paired rows. The rows of perlite bags were perpendicular to the central axis of the greenhouse, and there was a total of 40 rows, each 21 m in length; the rows were organized as 20 paired rows. The crop density was 2 plants m^{-2}.

Seedlings were transplanted into the perlite bags before the inflorescence of the first truss was visible, and the plants were supported vertically by nylon cord guides. All auxiliary shoots were removed, leaving only the main stem, which was topped (apex removed) at 99, 97, and 197 days after transplanting (DAT) for the Autumn, Spring, and Long Cycle crops, respectively, when there were 7, 8, and 18 trusses per plant. The plastic cover of the greenhouse was whitewashed ($CaCO_3$ suspension applied) from 0 to 20 DAT in the Autumn crop, from 37 DAT until the end of the crop in the Spring crop, and twice in the Long Cycle crop, from 0 to 20 DAT and from 154 DAT until the end of the crop.

Nutrient and irrigation management were consistent with local commercial practices. Complete nutrient solutions (Table 1) were applied in all irrigations throughout the crop through a drip irrigation system (five emitters per bag, discharge rate of 2 L h^{-1}). Before adding nutrients, the irrigation water had an electrical conductivity (EC) of 1.8–2.2 dS m^{-1}. The frequency of irrigation was controlled by a demand tray system equipped with a water level sensor [3]. The drainage fraction (volume of drainage divided by volume of water applied) was adjusted to maintain the EC of the drainage at ≤5 dS m^{-1} (Table 1), which resulted in a drainage fraction of 37–44% [30].

Table 1. Characteristics and composition of the nutrient solution and drainage in the three tomato crops. The concentrations of macronutrients are expressed in mmol L^{-1}, micronutrients in mg L^{-1}, and EC in dS m^{-1}. All values are averages for each crop cycle.

	Crop	EC	pH	Macronutrients (mmol L^{-1})							Micronutrients (mg L^{-1})				
				NO_3^-	PO_4^{3-}	SO_4^{2-}	NH_4^+	K^+	Ca^{2+}	Mg^{2+}	Fe	Mn	Zn	B	Cu
Supply	Autumn	3.4	6.0	9.0	1.7	3.0	1.2	7.0	4.8	2.6	2.1	1.8	0.6	0.4	0.1
	Spring	3.3	6.2	9.9	1.5	3.1	0.9	6.1	4.6	2.7	1.7	1.6	0.4	0.3	0.1
	Long Cycle	3.5	6.3	9.2	1.4	3.3	0.8	6.1	4.9	2.8	1.4	1.3	0.3	0.1	0.1
Drainage	Autumn	5.2	6.2	8.5	1.9	5.8	0.1	8.0	7.2	5.0	3.2	2.0	0.8	0.6	0.2
	Spring	4.9	6.1	11.0	1.6	5.5	0.2	7.0	6.2	4.9	2.6	1.7	0.6	0.4	0.2
	Long Cycle	5.3	6.2	10.2	1.7	5.7	0.1	6.6	7.3	5.2	2.4	1.3	0.4	0.2	0.1

2.2. Experimental Design

The lines of plants and substrate bags in the greenhouse were organized into 20 paired rows. Three paired rows on each side of the crop were borders. Within the crop, there were two zones. One zone (Zone 1) with four paired rows was used for the nutrient balance method (see Section 2.3.3); there was no destructive plant sampling in this zone. The other zone (Zone 2), in which regular biomass sampling occurred (see Section 2.3.2), consisted of eight paired rows. The two zones were separated by a border of one paired row.

Half of the paired rows in each zone received conventional nutrient and irrigation management that was consistent with local commercial practice. The other paired rows in each zone received an improved nutrient management system described by Cedeño [30] that was not used in this study. Individual rows of plants and substrate bags were replicate plots. All measurements were made in each of four replicate plots (that is, in one row) per treatment.

2.3. Measurements

2.3.1. Climate

There was continual monitoring of climate parameters were inside the greenhouse. A ventilated psychrometer (PRIVA, De Lier, The Netherlands) was used to measure air temperature and relative humidity. A pyranometer (model SP 110, Apogee Instruments, Logan, UT, USA) measured solar radiation.

2.3.2. Determination of Nutrients Uptake in Dry Matter

Nutrient uptake for N, P, K, Ca, Mg, and S, using the dry matter method, was determined regularly throughout each crop. For the Autumn crop, nutrient uptake was determined seven times, for the Spring crop eight times, and for the Long Cycle crop 10 times. These numbers include the final biomass sampling at the end of each crop. To determine the nutrient uptake by the crop using the dry matter method, measurements of above-ground dry matter production were made by periodically harvesting two representative plants from each of the four replicate plots (Zone 2) and determining the amount of dry matter in the leaves, stems, and immature fruits. Dry matter determinations were made by weighing all fresh material of each component and by oven-drying representative samples at 65 °C until a constant weight was reached. Additionally, the amounts of all pruned shoot material and fruit production were determined throughout each crop, from the same nine marked plants in each of the four replicate plots. The mass of dry matter in the fruit and pruned material was determined as previously described. For each biomass sampling, total above-ground dry matter was determined from the sum of dry matter of the leaves, stems, and immature fruits for that sampling date, plus the combined dry matter of all pruned material and harvested fruit until that sampling date. Representative samples of dry matter of each plant component from each biomass sampling were finely ground by sequentially using a knife mill and ball mill. In the dried plant samples, total N content was determined with an elemental analyzer (Model TRUSPEC CN628, LECO Corporation, St. Joseph, MI, USA) and K, P, Ca, and Mg contents were determined by Inductively Coupled Plasma (ICP) spectrometry (Model ICAP 6500DUO, ThermoFisher Scientific, Waltham, MA, USA) after sample digestion.

For each plant component, on each sampling date, nutrient uptake was determined as the product of the dry matter and nutrient content. Above-ground crop uptake of each nutrient was calculated for each biomass sampling as the sum of uptake in the leaves, stems, and immature fruit, plus the uptake in the accumulated pruned and harvested fruits until that biomass sampling. Nutrient uptake determined using the dry matter method is expressed as kg per ha. The data presented are the means of the four replicate plots of crop nutrient uptake in biomass.

2.3.3. Determination of Nutrient Uptake with the Mass Balance Method

The determination of nutrient uptake with the mass balance method firstly involved measurement of the volumes of the applied nutrient solution (i.e., irrigation) and of drainage, as described by Cedeño et al. [30]. Irrigation volume was measured using a water volume meter. Drainage was collected from four drainage trays (3 m long × 0.4 m wide × 0.1 m high) positioned in different rows (i.e., plots) in the non-destructive sampling area (Zone 1). In each drainage tray, there were two perlite bags, each containing a total of six plants and 10 drippers. Drainage from each tray was collected in a 20 L container.

Every weekday, at 8:00, prior to initiating irrigation for the day, the volume of nutrient solution (i.e., irrigation) applied, in the previous 24 h, was measured by reading the water meter. This was done for each of the three crops. The volume of drainage collected in each 20 L container for the previous 24 h was also measured at 8:00 every weekday. The cumulative volumes of irrigation and drainage of Friday, Saturday, and Sunday were measured the following Monday at 8:00. Daily crop water uptake was determined as the difference between the daily volumes of applied nutrient solution and drainage.

From the daily samples of nutrient solution and drainage, composite samples from each plot were prepared for two-weekly periods by mixing representative sub-samples of the daily/weekend samples in proportions relative to the volumes of the individual daily samples collected. The nutrient concentrations in the two-weekly composite samples were determined using ion chromatography (model 850, Professional IC Cation, Methrom AG., Herisau, Switzerland) for anions (NO_3^- PO_4^{3-} and SO_4^{2-}), and Inductively Coupled Plasma (ICP) spectrometry (model ICAP 6500DUO, ThermoFisher Scientific, MA, USA) for cations (NH_4^+, K^+, Ca^{2+}, Mg^{2+}).

The amount applied of each nutrient was determined every two weeks as the product of the volume applied and the concentration in the composite sample for the same two-week period. Similarly, the amount of each nutrient drained was the product of the drainage volume and the concentration in the composite drainage sample for the same two-week period.

The crop uptake of each nutrient was calculated for each two-week period as the amount of nutrients applied minus the amount drained. Crop uptake values, determined using the balance method, were the mean values of the four replicate plots. Cumulative crop uptake was obtained by sequentially summing the uptake for sequential two-week periods. Nutrient uptake determined using the balance method is expressed as kg ha^{-1}.

2.3.4. Determination of Nutrient Retention in Perlite Substrate

Nutrient retention in perlite was determined for a given crop as the difference between the total nutrient contents at the end and the beginning of the crop. This determination was conducted for the Autumn and Long Cycle crops. The nutrient content was determined by sampling one perlite bag from each of the four replicate plots. Six samples were taken from each bag with a 5 cm diameter auger to the bottom of the bag. Three locations were next to drip emitters, and three locations were between drip emitters. Prior to sampling, the bags did not receive any nutrient solution for 24 h to ensure drainage had ceased. After sampling, the six samples from each bag were mixed to form a composite sample. The composite perlite samples were dried at 65 °C for 48 h. Visible root material was then manually removed. A representative sub-sample of approximately 150 g was ground in a ball mill. Total nutrient contents were determined using the methods described for plant material in Section 2.3.2, following digestion. The mass of nutrients on an area basis was calculated as the product of the amount of dry perlite per ha and the nutrient content in the dry substrate.

2.3.5. Estimation of Nutrient Uptake by Roots

The daily root biomass was calculated, using an adaptation of the VegSyst model [37], as a fraction of the aerial dry matter production [38]:

$$\mathrm{DMP}i_{\mathrm{roots}} = \mathrm{Ri} * \mathrm{DMP}i_{\mathrm{plant}} \quad (1)$$

where, for a given day (i), $\mathrm{DMP}i_{\mathrm{roots}}$ is the root dry matter production of that day (kg ha^{-1}), $\mathrm{DMP}i_{\mathrm{plant}}$ (kg ha^{-1}) is the above-ground dry matter production, and R (dimensionless) is the ratio between $\mathrm{DMP}i_{\mathrm{roots}}$ and $\mathrm{DMP}i_{\mathrm{plant}}$. In this model, the $\mathrm{DMP}i_{\mathrm{plant}}$ was simulated daily with the VegSyst model as described for tomato by Gallardo et al. [37].

The Ri parameter was calculated as:

$$\mathrm{Ri} = \mathrm{RS}_{\mathrm{max}} - (\mathrm{RS}_{\mathrm{max}} - \mathrm{RS}_{\mathrm{min}}) * \left(\frac{\mathrm{f}_{\mathrm{i-PAR}}}{\mathrm{f}_{\mathrm{f}}}\right) \quad (2)$$

where $\mathrm{RS}_{\mathrm{max}}$ and $\mathrm{RS}_{\mathrm{min}}$ (dimensionless) represent respectively the maximum and minimum ratios of $\mathrm{DMP}i_{\mathrm{roots}}$ to $\mathrm{DMP}i_{\mathrm{plant}}$. $\mathrm{f}_{\mathrm{i-PAR}}$ is the fraction of daily Photosynthetically Active Radiation (PAR) interception, and f_{f} is the maximum fraction of PAR intercepted by the crop, as described by Gallardo et al. [37].

The value of $\mathrm{RS}_{\mathrm{min}}$ was experimentally determined by sampling 25 tomato seedlings and separately measuring the dry matter of the roots and of the aerial part. Dry matter determinations were made by weighing all fresh material of each component and then oven-drying the samples at 65 °C until a constant weight was achieved. The value of $\mathrm{RS}_{\mathrm{max}}$ was obtained from E. Heuvelink, Wageningen University and Research (personal communication).

The uptake of a given nutrient by the roots for a given day was determined as the product of $\mathrm{DMP}i_{\mathrm{roots}}$ and the nutrient content in the roots. Root nutrient uptake was determined in this way for N, P, K, Ca, and Mg.

At the time of maximum crop growth, four complete plants of tomato were sampled. The roots were carefully removed from the perlite substrate, and then washed and dried. Samples were finely ground using sequentially a knife mill and ball mill, and then analyzed. The nutrient contents of root samples were determined as follows. Total N content was determined with an elemental analyzer (Model TRUSPEC CN628, LECO Corporation, MI, USA). The contents of K, P, Ca, and Mg were determined by Inductively Coupled Plasma (ICP) spectrometry (Model ICAP 6500DUO, ThermoFisher Scientific, MA, USA) after sample digestion. For each nutrient, root uptake was calculated as the product of estimated total root dry matter production ($\mathrm{DMP}i_{\mathrm{roots}}$) and the root nutrient content, which was considered to be equivalent to the value determined at maximum crop growth.

3. Results

3.1. Climate

The mean seasonal values of daily average, maximum, and minimum temperatures were similar for the Autumn and Long Cycle crops (Table 2). The mean daily average temperatures for these two crops were 16.2–16.9 °C. In contrast, in the Spring crop, mean values for daily average, maximum, and minimum temperatures were 2.0–3.9 °C higher than in the other two crops. The mean values for the daily integral of solar radiation were also similar for the Autumn and Long Cycle crops, being 6.4 and 6.1 MJ m^{-2} d^{-1} (Table 2). The equivalent value for the Spring crop was appreciably higher, being 10.1 MJ m^{-2} d^{-1}. The mean average daily mean vapor pressure deficit was similar in the Autumn and Long Cycle crops, being 0.73 and 0.76 kPa, respectively. The equivalent value was notably higher in the Spring crop, being 0.90 kPa.

Table 2. Mean values, for the duration of each crop, of daily average, maximum, and minimum air temperature and vapor pressure deficit (VPD), and of the daily integral value of solar radiation inside the experimental greenhouse.

Crop	Mean of Daily Climatic Values for Duration of Each Crop						
	Air Temperature (°C)			VPD (kPa)			Solar Radiation (MJ m^{-2} d^{-1})
	Average	Maximum	Minimum	Average	Maximum	Minimum	Integral
Autumn	16.9	24.8	12.3	0.73	1.99	0.08	6.4
Spring	20.1	27.2	14.2	0.90	1.71	0.01	10.1
Long Cycle	16.2	24.6	12.2	0.76	1.95	0.23	6.1

3.2. Nitrogen

Throughout most of the Autumn and Spring crops, the values of crop N uptake determined using the balance method were generally consistently higher than values determined using the dry matter method (Figure 1). The relative differences in crop N uptake between the two methods were generally similar in both the Autumn and Spring crops (Figure 1). In the Long Cycle crop, which was grown after the other two crops, there were no consistent differences in the values of crop N uptake measured by the two methods (Figure 1).

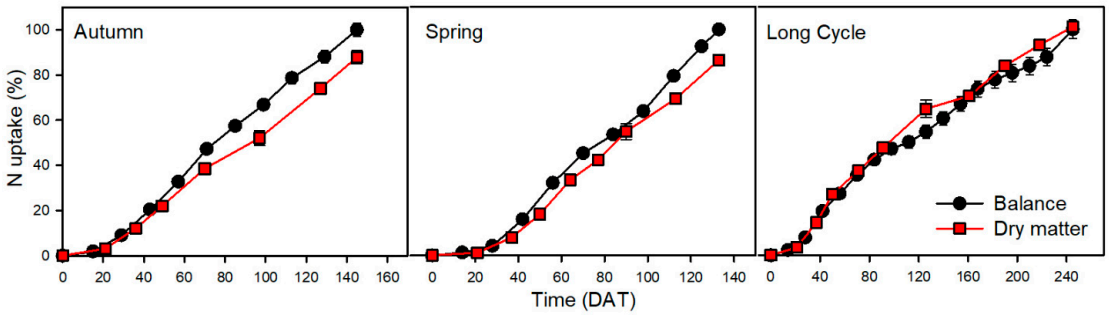

Figure 1. Seasonal evolution of the relative crop N uptake measured using the balance and the dry matter methods in the three consecutive crops (Autumn, Spring, and Long Cycle). Each value for both methods is relative to the final cumulative N uptake measured with the balance method. Data presented are means (n = 4) ± standard error (SE). DAT: Days After Transplanting.

Total crop N uptake at the end of the crops, determined by the dry matter method, was 88%, 86%, and 101% of that determined using the balance method in the Autumn, Spring, and Long Cycle crops, respectively (Table 3; Figure 1). The differences between methods in total N uptake in Autumn and Spring crops were statistically significant at $p \leq 0.05$ (Table 3). The relative differences (balance minus dry matter), with respect to the dry matter method, were 13%, 16%, and −1% for the Autumn, Spring, and Long Cycle crops, respectively (Table 3). As discussed in the Discussion, these amounts can be considered as additional nutrient consumed by the cropping system, in excess of that absorbed directly by the crop.

For N, there was a strong inverse linear relationship between the relative difference between the two methods (balance less dry matter), in relation to the dry matter method, and time the perlite substrate was used for cropping (Figure 2). This relationship was described by the linear regression equation, $y = -0.043x + 23.03$, $R^2 = 0.81$. Data relative to the dry matter method, rather than relative the balance method (Table 3), were used for this assessment for all nutrients, because values determined by the balance method apparently can be increased by different processes, as discussed in the Discussion section.

Table 3. Total crop N, P, K, Ca, Mg, and S uptake measured using the balance and the dry matter methods, and the absolute and relative differences between the two methods, in three consecutive tomato crops grown in perlite. The absolute difference is calculated as the balance method minus the dry matter method. The relative values of the differences between the two methods are presented in relation to the uptake determined by the balance method and the dry matter method. Analysis of variance (ANOVA) was used to assess the statistical significance of the differences between mean values of uptakes obtained using the two methods. The results of the ANOVA are presented as significant at $p \leq 0.05$ (*), very significant at $p \leq 0.01$ (**), highly significant at $p \leq 0.001$ (***), and not significant (ns).

Crop	Nutrient	Uptake by Balance Method (kg ha^{-1})	Uptake by Dry Matter Method (kg ha^{-1})	Statistical Significance of Difference between Methods	Difference—Balance Minus Dry Matter Method (kg ha^{-1})	Relative Difference (Relative to Balance Method) (%)	Relative Difference (Relative to Dry Matter Method) (%)
Autumn	N	278	245	*	33	12	13
	P	83	60	**	23	28	38
	K	448	307	***	141	31	46
	Ca	247	132	**	115	47	87
	Mg	57	27	***	30	53	111
	S	81	49	**	32	40	65
Spring	N	377	326	***	51	14	16
	P	112	77	***	35	31	45
	K	555	431	**	124	22	29
	Ca	367	202	***	165	45	82
	Mg	78	40	***	38	49	95
	S	120	79	**	41	34	52
Long Cycle	N	491	497	ns	−6	−1	−1
	P	135	106	*	29	21	27
	K	809	708	**	101	12	14
	Ca	428	367	ns	61	14	17
	Mg	86	67	ns	19	22	28
	S	162	141	ns	21	13	15

The retention of nutrients in perlite (column 5, Table 4) and the estimated uptake of nutrients by the roots (column 7, Table 4) were subtracted from the differences between methods (column 4, Table 4). The adjusted difference values are presented as residual differences in absolute and relative terms (columns 8 and 9, respectively, Table 4). For N, the residual difference between the two methods for determining uptake in the Autumn cycle was reduced to −3% (−9 kg N ha^{-1}) (columns 8 and 9, Table 4). However, in the Long Cycle, the difference between the two methods increased to −10% (−51 kg N ha^{-1}) (columns 8 and 9, Table 4). The amount of applied N retained in perlite represented 8 and 3% for the Autumn and Long Cycle crops, respectively (column 6, Table 4).

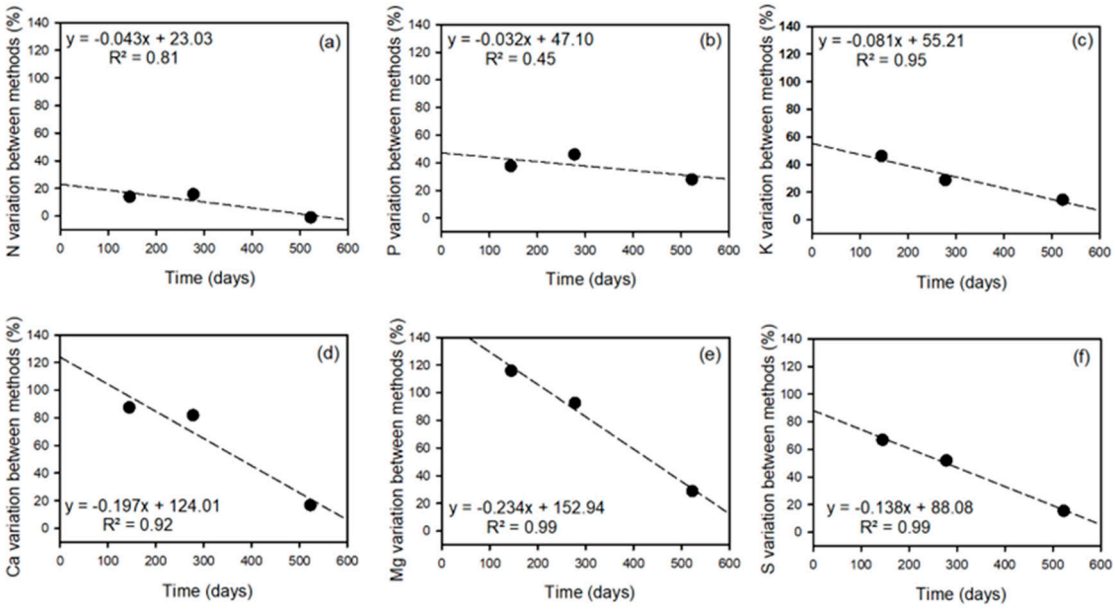

Figure 2. The relative difference between the two methods (balance less dry matter), in relation to the dry matter method, for (**a**) nitrogen, (**b**) phosphorus, (**c**) potassium, (**d**) calcium, (**e**) magnesium, and (**f**) sulfur, with time, during three consecutive tomato crops grown in perlite. Time is days of use of perlite for cropping. Equations of the linear relationship and R^2 values are presented for each nutrient in each panel.

Table 4. For N, P, K, Ca, Mg, and S in the Autumn and Long Cycle crops, the amount of nutrients applied, the absolute difference between nutrient uptake methods (balance minus dry matter), the measured retention of nutrients in the perlite, the percentage of applied nutrient retained in perlite, the estimated root nutrient uptake, the residual absolute difference between the two methods for determining nutrient uptake after considering nutrients retained in perlite and roots, and the relative residual difference in relation to uptake determined by the balance method.

Crop	Nutrient	Amount Applied (kg ha^{-1})	Difference in Uptake between Methods (kg ha^{-1})	Measured Retention in Perlite (kg ha^{-1})	Percentage of Applied Retained in Perlite (%)	Estimated Root Uptake (kg ha^{-1})	Residual Difference (kg ha^{-1})	Relative Residual Difference in Relation to Balance Method (%)
Autumn	N	405	33	32	8	10	−9	−3
	P	146	23	19	13	3	1	2
	K	776	141	77	10	10	54	12
	Ca	546	115	11	2	14	90	36
	Mg	182	30	18	10	2	10	18
	S	273	32	20	8	3	9	11
Long Cycle	N	908	−6	26	3	19	−51	−10
	P	286	29	22	8	6	1	0
	K	1554	101	44	3	20	37	5
	Ca	1266	61	29	2	28	4	1
	Mg	443	19	−2	0	3	18	21
	S	683	21	2	0	8	11	7

3.3. Phosphorus

The values of crop P uptake determined using the balance method were generally consistently higher than the values determined using the dry matter method throughout each of the three crops (Figure 3). The differences between the two methods were similar in

the Autumn and Spring crops. The differences throughout the Long Cycle were generally less than those observed in the two previous crops (Figure 3).

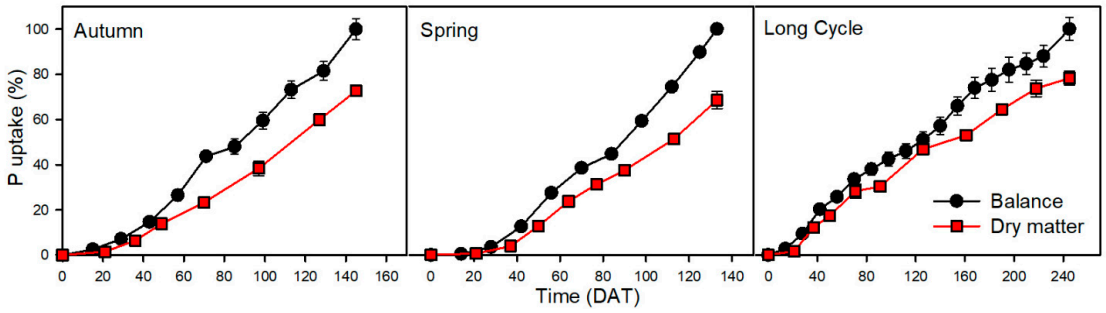

Figure 3. Relative crop P uptake determined using the balance and dry matter method in three consecutive tomato crops (Autumn, Spring, and Long Cycle) grown in perlite. In each crop, the final cumulative P uptake at the end of crop determined with the balance method represented 100% of relative crop P uptake. Data presented are means (n = 4) ± standard error (SE). DAT: Days After Transplanting.

Total P uptake values at the end of the crops determined with the dry matter method were 72%, 69%, and 79% of the equivalent values determined using the balance method for the Autumn, Spring, and Long Cycle crops, respectively (Table 3; Figure 3). The differences in total P uptake determined by the two methods were significantly different ($p \leq 0.05$) in the three crops (Table 3).

For P, there was an inverse linear relationship between the value of the relative difference between the two methods (balance method less dry matter method) in relation to the dry matter method, and time (Figure 2). This relationship was described by the equation $y = -0.032x + 47.10$, $R^2 = 0.45$.

The adjusted differences between the two methods, considering estimated root P uptake and accumulated P in perlite at the end of the Autumn and Long Cycle crops, were very close to zero (column 8 and 9, Table 4). The amount of applied P retained in perlite represented 13 and 8% of the applied P for the Autumn and Long Cycle crops, respectively (column 6, Table 4).

3.4. Potassium

Throughout most of the Autumn and Spring crops, the values of crop K uptake determined using the balance method were generally consistently higher than values determined using the dry matter method (Figure 4). The differences in determined crop K uptake, between the two methods, were slightly and consistently smaller in the Spring compared to the preceding Autumn crop (Figure 4). Throughout most of the Long Cycle crop, there were only small or negligible differences between the values of crop K uptake obtained with the two methods (Figure 4).

Total measured crop K uptake at the end of the crops was higher using the balance method compared to the dry matter method for the three crops (Table 3). The differences in total K uptake determined by the two methods were statistically very significantly different ($p \leq 0.01$) for the three crops (Table 3). Total K uptake determined by the dry matter method was 69%, 78%, and 88% of that determined using the balance method in the Autumn, Spring, and Long Cycle crops, respectively (Table 3; Figure 4).

For K, there was a very strong inverse linear relationship between the value of the relative difference between the two methods (balance method less dry matter method) in relation to the dry matter method, and time (Figure 2). This relationship was described by the equation $y = -0.081x + 55.21$, $R^2 = 0.95$.

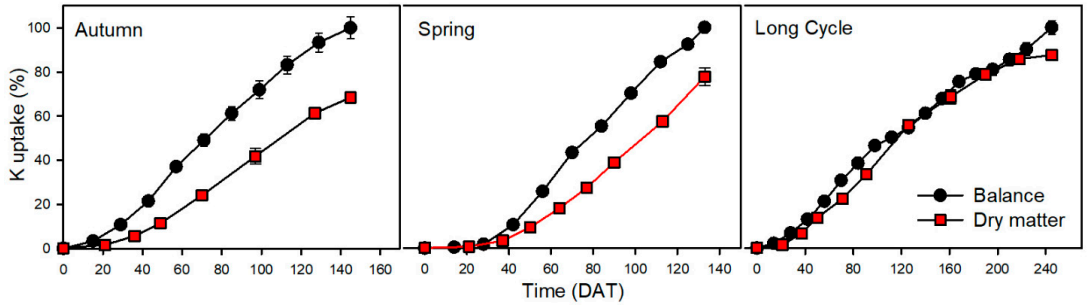

Figure 4. Relative crop K uptake determined using the balance method and dry matter method in three sequential crops (Autumn, Spring, and Long Cycle) of tomato, grown in perlite. In each crop, the final cumulative K uptake at the end of crop determined with the balance method represented 100% of relative crop K uptake. Data presented are means (n = 4) ± standard error (SE). DAT: Days After Transplanting.

Adjusting the differences between the two methods for retention in the perlite substrate and estimated root uptake reduced the difference to 12% (54 kg K ha^{-1}) in the Autumn crop and −5% (37 kg K ha^{-1}) in the Long Cycle crop (column 8 and 9, Table 4). The amount of applied K retained in perlite represented 10 and 3% for the Autumn and Long Cycle crops, respectively (column 6, Table 4).

3.5. Calcium

Throughout the Autumn and Spring crops, the values of crop Ca uptake determined using the balance method were considerably higher than values determined using the dry matter method (Figure 5). There were appreciable and consistent differences between the two methods in both the Autumn and Spring crops. The final measured Ca uptake using the dry matter method was 53–55% of that obtained using the balance method in the Autumn and Spring crops (Table 3; Figure 5). Throughout the Long Cycle crop, the values of Ca uptake determined by both methods were generally very similar (Figure 5). The differences between methods in total Ca uptake in the Autumn and Spring crops were statistically very significant at $p \leq 0.01$ (Table 3).

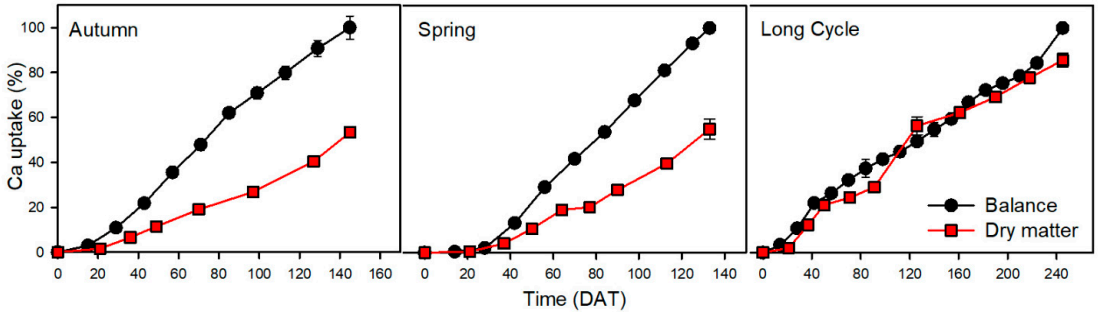

Figure 5. Relative crop Ca uptake determined using the balance method and dry matter method in three sequential crops (Autumn, Spring, and Long Cycle) of tomato, grown in perlite. In each crop, the final cumulative Ca uptake at the end of the crop determined with the balance method represented 100% of relative crop Ca uptake. Data presented are means (n = 4) ± standard error (SE). DAT: Days After Transplanting.

For Ca, there was a very strong inverse linear relationship between the value of the relative difference between the two methods (balance method less dry matter method) in relation to the dry matter method, and time (Figure 2). The relationship was described by the equation y = −0.20x + 124.01, R^2 = 0.92.

When using the adjusted difference between the two methods, which included estimated nutrient uptake in roots and nutrient accumulation in perlite, the difference in

the Autumn cycle was reduced to 36% (90 kg Ca ha^{-1}) in the Autumn crop and 1% (4 kg Ca ha^{-1}) in the Long Cycle crop (columns 8 and 9, Table 4). The amount of applied Ca retained in perlite represented 2% in each of the Autumn and Long Cycle crops (column 6, Table 4).

3.6. Magnesium

Throughout most of the Autumn and Spring crops, the values of crop Mg uptake determined using the balance method were generally consistently and appreciably higher than values determined using the dry matter method (Figure 6). The differences in estimated crop Mg uptake between the two methods were notably and consistently smaller in the Spring compared to the previous Autumn crop (Figure 6). Throughout most of the Long Cycle crop, the values of crop Mg uptake determined by the dry matter method were generally consistently slightly less than the values determined by the balance method (Figure 6).

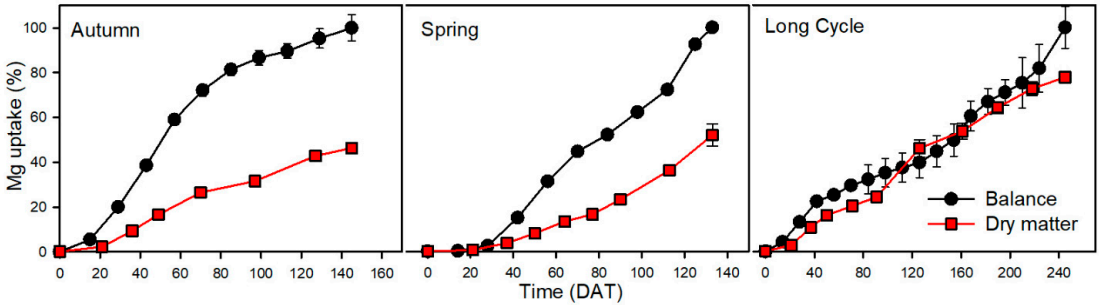

Figure 6. Relative crop Mg uptake determined using the balance method and dry matter method in three sequential crops (Autumn, Spring, and Long Cycle) of tomato, grown in perlite. In each crop, the final cumulative Mg uptake at the end of crop determined with the balance method represented 100% of relative crop Mg uptake. Data presented are means (n = 4) ± standard error (SE). DAT: Days After Transplanting.

In the Autumn and Spring crops, the total Mg uptake at the end of the crops determined by the dry matter method was 47% and 51% of that determined using balance method, respectively (Table 3; Figure 6). In the Long Cycle crop, total Mg uptake determined by the dry matter method was 78% of that determined using the balance method (Table 3; Figure 6). The differences in the determination of total crop Mg uptake between the two methods were statistically highly significant ($p \leq 0.001$) in the Autumn and Spring crops (Table 3).

For Mg, there was a very strong inverse linear relationship between the value of the relative difference between the two methods (balance method less dry matter method), in relation to the dry matter method, and time (Figure 2). The equation that described the relationship was $y = -0.23x + 0.152.94$, $R^2 = 0.99$.

When using the adjusted difference between the two methods, which included estimated nutrient uptake in roots and nutrient accumulation in perlite, the difference in the Autumn cycle was reduced to 18% (10 kg Mg ha^{-1}) in the Autumn crop and 21% (18 kg Mg ha^{-1}) in the Long Cycle crop (column 8 and 9, Table 4). The amount of applied Mg retained in perlite represented 10 and 0% for the Autumn and Long Cycle crops, respectively (column 6, Table 4).

3.7. Sulphur

Throughout the three crops, the values of crop S uptake determined using the balance method were generally consistently higher than those determined using the dry matter method (Figure 7). The differences were considerable for the Autumn crop, appreciable for the Spring crop, and relatively small for the Long Cycle crop. Total crop S uptake at the end of the crop determined using the dry matter method was 60%, 66%, and 87% of

that determined using the balance method for the Autumn, Spring, and Long Cycle crops, respectively (Table 3, Figure 7). The differences in total S uptake determined by the two methods were statistically very significantly different ($p \leq 0.01$) for the Autumn and Spring crops (Table 3).

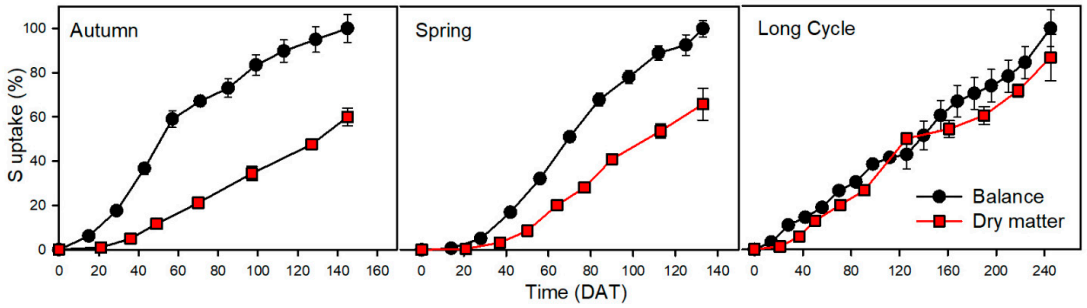

Figure 7. Relative crop S uptake determined using the balance method and dry matter method in three sequential crops (Autumn, Spring, and Long Cycle) of tomato, grown in perlite. In each crop, the final cumulative S uptake at the end of crop determined with the balance method represented 100% of relative crop S uptake. Data presented are means (n = 4) ± standard error (SE). DAT: Days After Transplanting.

For S, there was a very strong inverse linear relationship between the value of the relative difference between the two methods (balance method less dry matter method) in relation to the dry matter method, and time (Figure 2). This relationship was described by the equation $y = -0.138x + 88.08$, $R^2 = 0.99$.

When using the adjusted difference between the two methods, which included estimated nutrient uptake in roots and nutrient accumulation in perlite, the differences in the Autumn and Long Cycle crops were reduced to 11% (9 kg S ha^{-1}) and 7% (11 kg S ha^{-1}), respectively (columns 8 and 9, Table 4). The amount of applied S retained in perlite represented 8 and 0% for the Autumn and Long Cycle crops, respectively (column 6, Table 4).

4. Discussion

Higher values of nutrient (N, P, K, Ca, Mg, and S) uptake were consistently determined in the three crops using the balance method than with the dry matter method. The difference between the two methods for determining uptake of N, P, K, Ca, Mg, and S decreased progressively during the sequence of three crops. Higher values of nutrient uptake for N, P, K, Ca, Mg, and S were also determined by the balance method compared to the dry matter method for tomato grown in rockwool, in The Netherlands, by Voogt [35]. Also in The Netherlands, nutrient uptake determined using the balance method was higher than that determined by the dry matter method, when using a substrate-free Nutrient Film Technique (NFT), in young tomato plants [36]. In contrast, in a study with tomato in perlite, there were inconsistent differences between the two methods for the determination of uptake of N, Ca, Mg, or S [39]. However, in the study of San Juan-Delmas et al. [39] there was a notable degree of variation in the results which may have affected the comparison between methods [39].

The higher values of nutrient uptake obtained by the balance method compared to the dry matter method in the present work, and by Voogt [35] and Heisen et al. [36], are consistent with several recent studies that determined nutrient uptake concentration by the same two methods [40–43]. Uptake concentration is the uptake of a given nutrient divided by water uptake over the same time period [26–29]. In tomato, cucumber, and eggplant, the uptake concentrations of N, P, and Ca were clearly higher when using the balance method to determine crop nutrient uptake [40]. In another study with tomato, the uptake concentrations of N, K, and Ca were higher when determined with the balance method than with the dry matter method [42]. During the vegetative stage of a tomato crop, uptake concentrations of P, K, and Mg were higher when using the balance method

to determine crop nutrient uptake [41]. Xaxiri et al. [40] suggested that precipitation and gaseous N losses were responsible for the higher uptake concentration values determined using the mass balance method compared to the dry matter method.

The determination of nutrient uptake using the dry matter method in the present study did not include direct determination root nutrient uptake. Simulation of the nutrient uptake by the roots with an adaptation of the VegSyst model [37] suggested that the amounts of nutrients in the roots were very small. This agrees with experimental data from tomato, grown in substrate, where roots contained less than 2% of crop nutrient consumption [44].

In the present study, determination of the nutrient content in perlite before and after each crop indicated notable retention of nutrients in the perlite during the three sequential crops. The measured amounts of nutrients retained in the perlite did not account for all of the differences between the two methods. However, they indicated that direct retention of nutrient in the perlite substrate occurred. Similarly, Sanjuan-Delmás et al. [39] reported that the nutrients directly retained in perlite represented a notable percentage of the total uptake, estimated by the balance method, representing up to 7% for N, 6% for P, 1% of K, 7% for Ca, 5% for Mg, and 2% for S [39]. Xiong et al. [45] reported that, of the nutrients applied to a tomato crop in rockwool, 3% of N, 2% of P, 5% of K, 18% of Ca, 36% of Mg, and 4% of S were retained in the substrate. The direct retention in perlite in the Long Cycle Crop (0–8%) and the Autumn crop with new perlite (2–13%) in the present study were generally consistent with the retention values reported by Sanjuan-Delmás et al. [39] and Xiong et al. [45]. Rivera-del Rio et al. [46] compared nutrient retention in different substrates and reported that the highest retention occurred in perlite compared to coconut fiber and tenxontle, a local substrate used in Mexico. Vandercasteele et al. [47] determined appreciable retention of P, K, Ca and Mg in rockwool.

In the present study, the difference between the two methods in nutrient uptake decreased progressively with the sequence of crops. Similarly, the measured retention of nutrients in perlite progressively reduced. This suggests that the apparent capacity to retain nutrients is largest in new perlite substrate and declines with time. We are unaware of publications reporting the effect of substrate age on nutrient retention. While these regressions would have been stronger with more data points, they provide clear indications of the tendencies with time of the relative differences between the two methods. It is suggested that future work make a more detailed analysis of the changes with time of the relative differences between the two methods.

The present study, together with the available scientific literature, suggests that, in soilless cropping, values of nutrient uptake determined by the mass balance method generally exceed those determined by the dry matter method. The processes responsible are not clearly understood, but processes such as precipitation [40,41], direct retention on substrate, and gaseous losses of N and S [34] are likely to be involved. In the present study, there were a small number of instances (e.g., K in the Autumn and Long Cycle crops, Ca in the Autumn crop) where the values for the residual difference, after considering perlite and root retention, were high (Table 4). These data may indicate a need to improve the methodology for sampling and analyzing the perlite substrate.

The results reported in this work demonstrate the necessity to differentiate between nutrient uptake of a crop and nutrient consumption of a growing system, as was commented by Neocleous and Savvas [41] and by Xaxiri et al. [40]. The dry matter method estimates nutrient uptake of the crop. The balance method estimates nutrient consumption of the growing system, as it includes factors that effectively reduce nutrient availability to the crop [40,41]. Suggested processes are precipitation, direct nutrient retention in the substrate, and gaseous losses. These processes serve to increase the apparent nutrient uptake, which is the nutrient consumption of the growing system. Further research is required to understand and quantify these processes in different substrates and how they respond to substrate age.

When developing nutrient recommendations for substrate-grown crops, it is suggested that nutrient consumption of the growing system should be considered rather than nutrient uptake within dry matter of the crop. Nutrient consumption of the growing system includes

the precipitation, retention, and gaseous losses referred to in the previous paragraphs. Nutrient consumption of the growing system can be determined in two ways: (1) by using the balance method, or (2) by using the dry matter method with additional numerical factors for the apparent "nutrient loss" caused by the growing system. The latter approach would be well-suited to modeling approaches used in decision support systems thereby enabling estimation of nutrient consumption for different substrates by considering the substrate and the effect of substrate age.

The consumption of nutrients by growing systems that is additional to the nutrients directly absorbed in plant biomass has important implications for nutrient management of substrate-grown crops, where a high degree of control over nutrition is required to fully optimize production. There is a pressing requirement for further research to improve knowledge and quantification of the factors responsible for the observed differences between nutrient consumption estimated by the balance and dry matter methods for determining nutrient use of substrate-grown crops.

5. Conclusions

Crop nutrient uptake determined using the balance method was consistently higher than with the dry matter method. The relative differences (balance minus dry matter) were N: −1 to 16%, P: 27–45%, K: 14–46%, Ca: 17–87%, Mg: 28–111%, and S: 15–65%, with respect to the dry matter method. The differences between the two methods reduced with successive crops. The higher estimates of nutrient consumption with the balance method compared to the dry matter method are consistent with other studies with substrate-grown crops. These results suggest that the dry matter method provides an estimate of nutrient consumption by the crop, whereas the balance method provides an estimate of nutrient consumption by the cropping system. It is suggested that the latter is more relevant for practical nutrient management of substrate-grown crops.

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