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Crop and Irrigation Management Systems under Greenhouse Conditions

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Received: 21 November 2017; Accepted: 9 January 2018; Published: 11 January 2018

Abstract: Plants of *Ruscus aculeatus*, known as "butcher's broom", *Maytenus senegalensis*, known as "confetti tree", and *Juncus acutus*, known as "spiny rush" were grown in pots with a mixture of sphagnum peat-moss and Perlite in order to determine the effect and evolution over time of three water use systems on plant growth, water saving and nutrient uptake. These were an open system (irrigated with standard nutrient solution) and two closed systems (blended-water (drainage water blended with water of low electrical conductivity (EC)) and sequential reuse of drainage (sequential-reuse) water), over a period of 8 weeks. Irrigation with blended- and sequential-reuse-water increased the biomass of all three species at the end of the experiment, compared to the open system. Overall, sequential-reuse-water treatment maximised biomass production. The application of blended- and sequential-reuse-water allowed savings of 17% of water in comparison to the open system. Regarding Cl, NO_3^- and $H_2PO_4^-$ loads, there was a removal of 5%, 32% and 32%; respectively in the blended-water treatment and 15%, 17% and 17% in the sequential-reuse water treatment compared to the open system. For the cation loads (Na^+, K^+, Ca^{2+} and Mg^{2+}) in these water treatments there was a removal of 10%, 32%, 7% and 18% respectively in the blended-water treatment, and 17%, 22%, 17% and 18% respectively in the sequential-reuse treatment, compared to the open system.

Keywords: blending water; drainage water; electrical conductivity; ornamental potted plants; water-sequential reuse

1. Introduction

Growing plants in greenhouses can result in excessive leaching of nutrients from containerized crops grown in soilless substrate if irrigation is not managed properly [1]. The drainage water frequently contains high concentrations of nitrates, phosphorus and potassium [2]. Leakage of nitrate and phosphorous from irrigation in greenhouses to the environment was found to be considerably higher than recommended by environmental guidelines and caused pollution of surface and groundwater [3,4]. Moreover, the drainage shows an increase of electrical conductivity due to the accumulation of Na^+ and Cl^- where the original source of water contains these elements, even in low concentrations [5]. However, the drainage from irrigation of one species could be used to irrigate other species in a sequential process, providing the other crops being irrigated are suitably salt tolerant [6]; the drainage water could be used directly, or by blending it with the primary source of water available for the greenhouse operation.

The net volume of water used may be substantially reduced by the capture and reuse of drainage water on farms or in greenhouses. Additionally, the volume of high quality (low conductivity) water used can be reduced by blending with water of lower quality—water containing NaCl, for example. Methods for the use of saline drainage water have been developed in different countries [7–9]. These methods include blending and sequential-reuse from species to species. Blending is based on the combination of two sources of irrigation water to produce irrigation water of suitable quality while increasing the overall irrigation water supply. Nevertheless, it is not economically useful if the saline water cannot supply at least 25% of the total irrigation water requirement [10]. Blending drainage water with water of low electrical conductivity (EC) is widely practiced in large areas of Egypt, India, Pakistan, the United States, and Central Asia [11]. For field agriculture, sequential reuse involves application of water of better quality to the crop with the lowest salt tolerance, then using the drainage water from that field obtained from subsurface drainage system to irrigate crops with greater salt tolerance. In California, sequential reuse experiments have involved the use of trees, shrubs and grasses [12]. Nowadays, the recent focus is on forage cropping systems [13]. On a smaller scale, the sequential reuse system has been applied in greenhouses for crop irrigation in the Netherlands [14].

We investigated the potential for use of sequential irrigation with three species: *Ruscus aculeatus* L., *Maytenus senegalensis* Lam Exell and *Juncus acutus* L. Torr. All species are native to the Mediterranean area and have commercial value [15–17] but different degrees of salt tolerance. According to the recommendations given by local nursery growers: *R. aculeatus* is salt sensitive, *M. senegalensis* is salt tolerant and *J. acutus* is a halophyte. Nevertheless, there is no published data about the implementation of different irrigation methods or effects on yield of these species grown in greenhouses in the Mediterranean Basin Area. Therefore, in this study, a pot experiment with *R. aculeatus*, *M. senegalensis* and *J. acutus* was established in order to determine the effects of different water treatments on plant growth, water saving and nutrient removal. We established a model that allows growers to calculate the number plants and the water supplies needed in each water system from data on water uptake and the degree of salt tolerance of each species. The establishment of these water systems by growers would generate a water and nutrient saving together with the production of more saleable plants.

2. Materials and Methods

2.1. Experimental Design

A series of experiments under similar conditions was carried out on *R. aculeatus* (*Ra*), *M. senegalensis* (*Ms*) and *J. acutus* (*Ja*) plants during the spring of two consecutive years (2013–2014) in the facilities of the University of Almeria (36°49′ N, 2°24′ W). Plants were obtained from a commercial nursery and then transplanted into 1.5 L polyethylene pots filled with a mixture of sphagnum peat-moss and Perlite 80:20 (*v*/*v*) and grown in a greenhouse of 150 m^2. During the spring, the microclimatic conditions inside the greenhouse were monitored continuously with HOBO SHUTTLE sensors (model H 08-004-02, Onset Computer Crop., Bourne, MA, USA). Average day temperature was 17.1 °C, relative humidity (RH) 65.6% and photosynthetically active radiation (PAR) 6.2 mol m^{-2} day^{-1}. All the experiments lasted 8 weeks, which corresponds to the time necessary to produce saleable plants of all three species following the recommendations given by local growers.

2.2. Experimental Water Treatments

The experiment consisted of four replicates with four plants (one plant per pot) per species and stage with a planting density of 10 plants per m^2, and three water systems: an open system irrigated with standard nutrient solution (O) and two closed systems (blended—(B) and sequential-reuse (S) water treatments). The standard nutrient solution (water number 1, Table 1) was prepared according to the recommendations given by Jimenez and Caballero [18] for the optimum growth of ornamental plants under Mediterranean conditions and was derived from tap water with the following composition (in mmol L^{-1}): 1.1 SO_4^{2-}, 3.50 Cl^-, 2.00 Ca^{2+} and 1.40 Mg^{2+} and electrical conductivity of 0.9 dS m^{-1}. The drainage collected in the open system was not reused and was discharged to the environment. In the two closed systems, *R. aculeatus* plants (first stage) were irrigated with the standard nutrient solution (water number 1) already described, but in each closed system the drainage generated by this species was used in a different way. In the blended water treatment, the drainage of *R. aculeatus* plants was blended 50/50 with tap water (water number 2) to irrigate *M. senegalensis* plants, from which the drainage generated (water number 3) was reused to irrigate *J. acutus* plants. In the sequential reuse water treatment, the drainage of *R. aculeatus* plants without blending (water number 4) was used to irrigate *M. senegalensis* plants, from which the drainage generated (water number 5) was reused to irrigate *J. acutus* plants. Both blended and sequential reuse water treatments were characterized by no drainage discard from *J. acutus* plants (Figure 1).

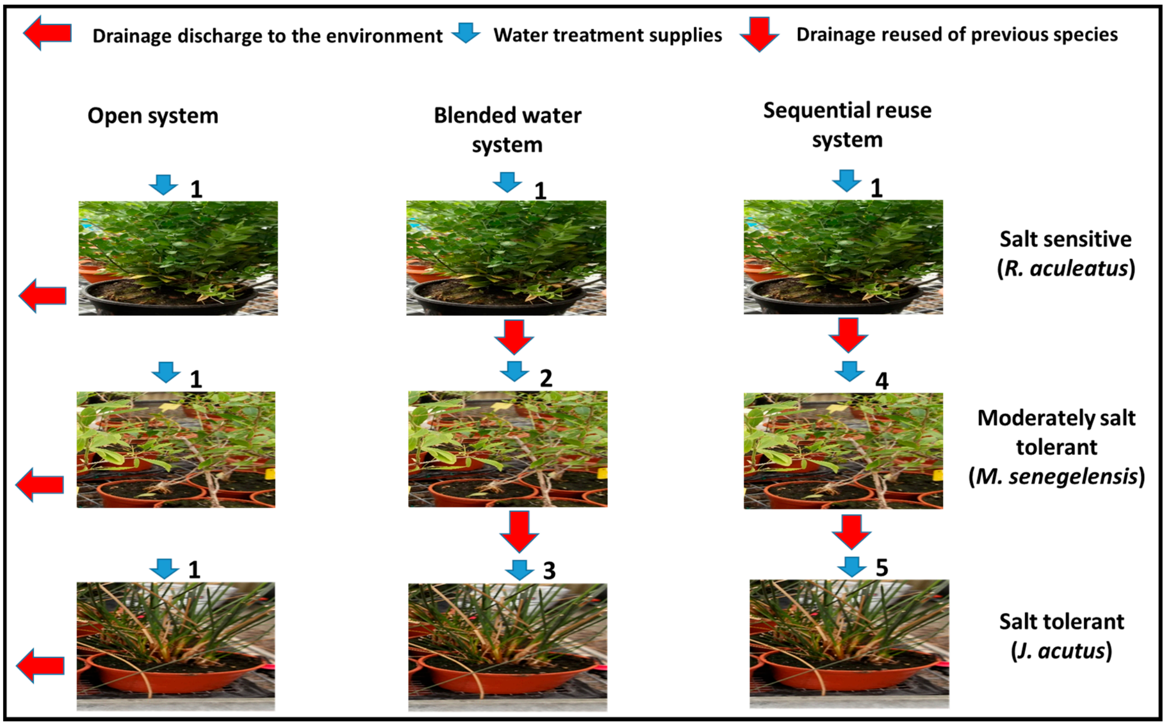

Figure 1. General layout of the different experimental water treatments in order to determine the effect of using drainage water on growth and nutrient removal by three native species. Water number 1: standard nutrient solution; number 2: blend of tap water and drainage from irrigation of *R. aculeatus* with nutrient solution used to irrigate *M. senegalensis*; number 3: drainage from irrigation of *M. senegalensis* irrigated with water number 2 used to irrigate *J. acutus*; number 4: drainage from irrigation of *R. aculeatus* with nutrient solution used to irrigate *M. senegalensis*, and number 5: drainage from irrigation of *M. senegalensis* irrigated with water number 4 used to irrigate *J. acutus*.

2.3. Plant Height and Biomass

Prior to the initiation of the water treatments and at the end of the experiment (8 weeks), four plants per species and per water treatment were selected to determine plant height. Plant height was measured from the top edge of the pot to the youngest open leaf of the plant crown, using a ruler. Then these selected plants were harvested and the substrate gently washed from the roots. The plants were divided into shoots and roots: the surface of the roots was dried with blotting paper prior to weighing. Shoots and roots were then oven-dried at 60 °C for 48 h to determine respective dry weights (DW). The total biomass for each species was calculated as the sum of shoots and roots. Finally, in order to compare the data of biomass among water systems, the total biomass of each system (expressed in g) was calculated by multiplying the total biomass of all species in the system by the planting density and distribution ratio of each system, respectively.

Table 1. Chemical composition of the applied water. Electrical conductivity (EC) was expressed in dS m^{-1} and nutrient concentration in mmol L^{-1}. Water number 1: standard nutrient solution; number 2: blend of tap water and drainage from irrigation of *Ra* with nutrient solution used to irrigate *Ms*; number 3: drainage from irrigation of *Ms* irrigated with water number 2 used to irrigate *Ja*; number 4: drainage from irrigation of *Ra* with nutrient solution used to irrigate *Ms*, and number 5: drainage from irrigation of *Ms* irrigated with water number 4 used to irrigate *Ja*. Data are the means ± standard deviation of four samples per treatment. For water numbers 2–5, the values are the average values of the different chemical parameters analyzed weekly during the trial.

Chemical Parameters	Water Applied for Irrigation				
	1	2	3	4	5
pH	6.5	7.9 ± 0.2	7.5 ± 0.2	7.7 ± 0.2	7.5 ± 0.3
EC	1.5	2.2 ± 0.2	3.2 ± 0.3	2.9 ± 0.3	3.9 ± 0.4
NO_3^-	6.0	2.6 ± 0.4	3.3 ± 0.4	3.5 ± 0.3	4.1 ± 0.4
$H_2PO_4^-$	0.7	0.03 ± 0.01	0.06 ± 0.02	0.04 ± 0.01	0.03 ± 0.01
Cl^-	3.5	11.5 ± 1.1	19.6 ± 1.8	17.6 ± 1.8	23.5 ± 2.0
SO_4^{2-}	2.0	3.4 ± 0.3	4.0 ± 0.4	3.5 ± 0.3	5.1 ± 0.5
Ca^{2+}	2.0	2.6 ± 0.2	4.0 ± 0.4	3.2 ± 0.3	4.6 ± 0.4
Mg^{2+}	1.4	1.8 ± 0.2	1.2 ± 0.1	1.3 ± 0.1	1.7 ± 0.2
K^+	3.0	2.7 ± 0.2	3.1 ± 0.3	3.0 ± 0.3	2.9 ± 0.3
Na^+	2.6	10.4 ± 1.3	21.1 ± 1.9	17.3 ± 1.6	25.6 ± 2.1

2.4. Sample Collection and Characterization

Drainage from each plant container was collected by placing a tight-fitting plastic collection container under each plant. Plant containers were elevated to prevent leachate from being reabsorbed into the container. Four samples of water supplies and drainage water generated in each stage of each water treatment were manually collected each week, filtered through 0.45-μm membranes and frozen until nutrient analyses were conducted. For each sample, electrical conductivity and pH values were recorded using models Milwaukee C66 and pH52, respectively (Milwaukee Instruments, Rocky Mount, NC, USA); and concentrations of nutrients were determined by high-performance liquid chromatography [HPLC (883 Basic IC Plus, anions ion exchange column Metrosep A SUPP 4, cations ion exchange column Metrosep C4 100, IC conductivity detector (0–15,000 μS cm^{-1}) Metrohm, Herisau, Switzerland)] as described by Csáky and Martínez-Grau [19]. Nutrient loads from each pot (in grams) were calculated by multiplying concentrations of nutrients by the volume of drainage water collected from each pot. Finally, in order to compare the volume of water (expressed in L) and nutrient loads (expressed in g) among water systems, the volume of water and nutrient loads of each water treatment were multiplied by planting density and distribution ratio of each irrigation treatment, respectively.

2.5. Statistical Analysis

The experiment was analysed as a completely randomized design. The Analyses of Variance (ANOVA) and the Fisher's Least significant difference (LSD) tests ($p < 0.05$) were used to assess the differences between water treatments. All statistical analyses were performed using Statgraphics Centurion XVI.II (Statpoint Technologies, Inc. Warrenton, VA, USA). Previously, normality was verified using the Shapiro-Wilk test, and homogeneity of variance was tested using the Bartlett test. Differences were considered significant at $p < 0.05$.

3. Results

3.1. Model Development

The aim of the establishment of this model was to determine the number of plants and the water supplies needed in each water system through the use of a series of inputs, in order to reduce the volume of water and nutrients used in the fertigation of ornamental plants—but always from the point of view of production of saleable plants.

Data used for the model and its calibration were collected during the first experiment in the spring of 2013 and the validation of the model was carried out in the spring of 2014. The main inputs of this model are the following: water uptake of the species in each stage of the different water systems ($Wupt_i$), percentage of leachate in the previous stage of the different drainage water systems ($Xlea_i$) and percentage of blending water (ID_i). The main outputs of the model are: number of plants needed in each stage of the different drainage water systems (P_i) and water supply for the species in each stage of the different drainage water systems ($Wsup_i$).

From the results obtained in these experiments, we defined the following equations in order to determine the number of plants needed in each stage of the different drainage water treatments (1) and the water supplies for the species in each stage of the different drainage water treatments (2):

$$P_i = \frac{P_{i-1} \times Wupt_{i-1} \times Xlea_{i-1} \times ID_{i-1}}{Wupt_i \times (1 + Xlea_i)} \tag{1}$$

$$Wsup_i = \sum_{i=1}^{n} P_i \times Wupt_i \tag{2}$$

The use of subscript ($_{i-1}$) refers to the previous stage in the different drainage water systems.

To determine the percentage of blending water (ID_i) in the previous equations, we used the following Equations (3)–(5): note that the value of ID_i in the sequential reuse water treatment is 1, so V_F is equal to V_{lea}.

$$V_{TW} = V_{lea} \times \frac{(EC_{lea} - EC_{mix})}{(EC_{mix} - EC_{TW})} \tag{3}$$

$$V_F = V_{lea} + V_{TW} \tag{4}$$

$$ID_i = \frac{V_{lea}}{V_F} \tag{5}$$

where, V_{TW} is the volume of tap water needed in the blended water treatment, EC_{lea} is the electrical conductivity of the leachate, EC_{TW} is the electrical conductivity of the tap water, EC_{mix} is the electrical conductivity of the mixture (leachate and tap water), V_{lea} is the volume of leachate and V_F is the total volume used in the blended water treatment. It is important to point out that the value of ID_i in the sequential reuse water treatment is 1, so V_F is equal to V_{lea}. The determination of EC_{mix} should be based on previous studies about the salt tolerance of each species ($_i$).

Finally, with the values obtained using Equations (1) and (2), we determined the distribution ratio (DR) of each species (expressed in number of plants per m^2) that can be grown in each water system. The values of DR in closed systems were: (B) (DR: 1/0.27/0.05) and (S) (DR: 1/0.11/0.03), which were also applied to the open system in order to compare the data obtained between water systems.

3.2. Chemical Composition of Water Treatments

pH and EC of waters No. 2, 3, 4 and 5 increased with respect to water No. 1 due to the increase in concentrations of Na^+, Cl^-, SO_4^{2-}, and Ca^{2+} and decrease in NO_3^- and $H_2PO_4^-$ (Table 1).

3.3. Plant Height and Biomass

Over the course of the experiment, the plants of all three species grew significantly in height and weight (Table 2) in the different water systems (open system (O) and closed systems (B and S). Additionally, the irrigation of *Ms* and *Ja* plants with S resulted in the highest values in both parameters.

The biomass of plants irrigated with B was higher than of those irrigated by O because of the increased biomass of *Ja*. In these plants subjected to S, the biomass of *Ms* and *Ja* was greater than under O irrigated with standard nutrient solution (Table 3).

Table 2. Plant height (cm) and dry weight (DW) (g plant^{-1}) at the beginning (Pb) and at end of the experiment (Pf). O—open system, B—blended water system, and S—sequential reuse system. Data are the means ± standard deviation of four plants per treatment. *Ra* = *Ruscus aculeatus*, *Ms* = *Maytenus senegalensis* and *Ja* = *Juncus acutus*. Averages within a file with the same letters are not significantly different at $p < 0.05$ (ANOVA and LSD test).

Parameters		**Pb**	**Pf**		
			O	**B**	**S**
Plant height	*Ra*	42.5 ± 4.5 b	61.7 ± 6.1 a		
	Ms	36.0 ± 3.2 c	58.75 ± 5.1 b	55.0 ± 4.9 b	69.2 ± 5.2 a
	Ja	46.0 ± 4.1 d	52.0 ± 4.6 c	56.0 ± 5.0 b	69.7 ± 5.8 a
DW	*Ra*	16.6 ± 1.6 b	24.6 ± 2.1 a		
	Ms	4.9 ± 0.5 c	9.6 ± 0.9 b	10.1 ± 1.0 b	12.7 ± 1.3 a
	Ja	13.6 ± 1.4 d	16.8 ± 1.3 c	31.4 ± 2.4 b	41.9 ± 3.5 a

Table 3. Biomass itemized by species plants subjected to three water treatments used as criterion to assess their respective distribution ratio (DR, distribution ratio of the number plants of the three species that can be grown in each water system). O—open system, B—blended water system, and S—sequential reuse system. Data are the means ± standard deviation of four plants per treatment. *Ra* = *Ruscus aculeatus*, *Ms* = *Maytenus senegalensis* and *Ja* = *Juncus acutus*. Averages within a column with the same letters are not significantly different at $p < 0.05$ (ANOVA and LSD test).

Distribution Ratio	**Water Systems**	**Dry Weight (g)**		
		Ra	***Ms***	***Ja***
DR (1:0.27:0.05)	O	246.4 ± 22.0 a	25.7 ± 2.5 a	8.4 ± 0.8 b
	B	246.4 ± 22.0 a	27.0 ± 2.1 a	15.7 ± 1.4 a
DR (1:0.11:0.03)	O	246.4 ± 22.0 a	10.6 ± 0.9 b	4.5 ± 0.4 b
	S	246.4 ± 22.0 a	15.1 ± 1.3 a	11.3 ± 1.1 a

3.4. Application of Model Development to Water Management

As far as total water volume and nutrient loads of each water system are concerned (Figure 2), the water system B resulted in a water saving of 17% compared to O (21.1 L in O and 17.6 L in B) and no generation of drainage with a volume of 4.9 L in O. In addition, the comparison between S and O resulted in a saving of water of 17% (17.2 L in O and 14.3 in S) and no generation of drainage with a volume of 3.9 L in O.

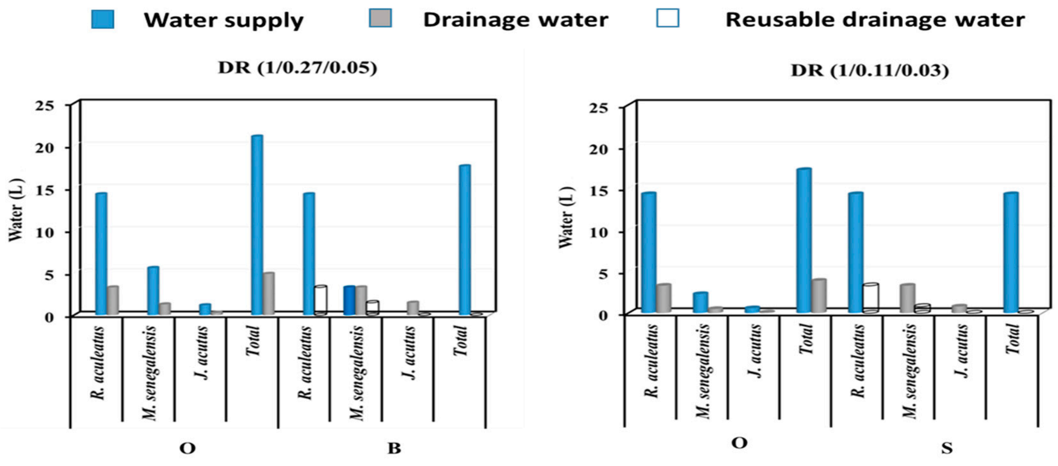

Figure 2. *Cont.*

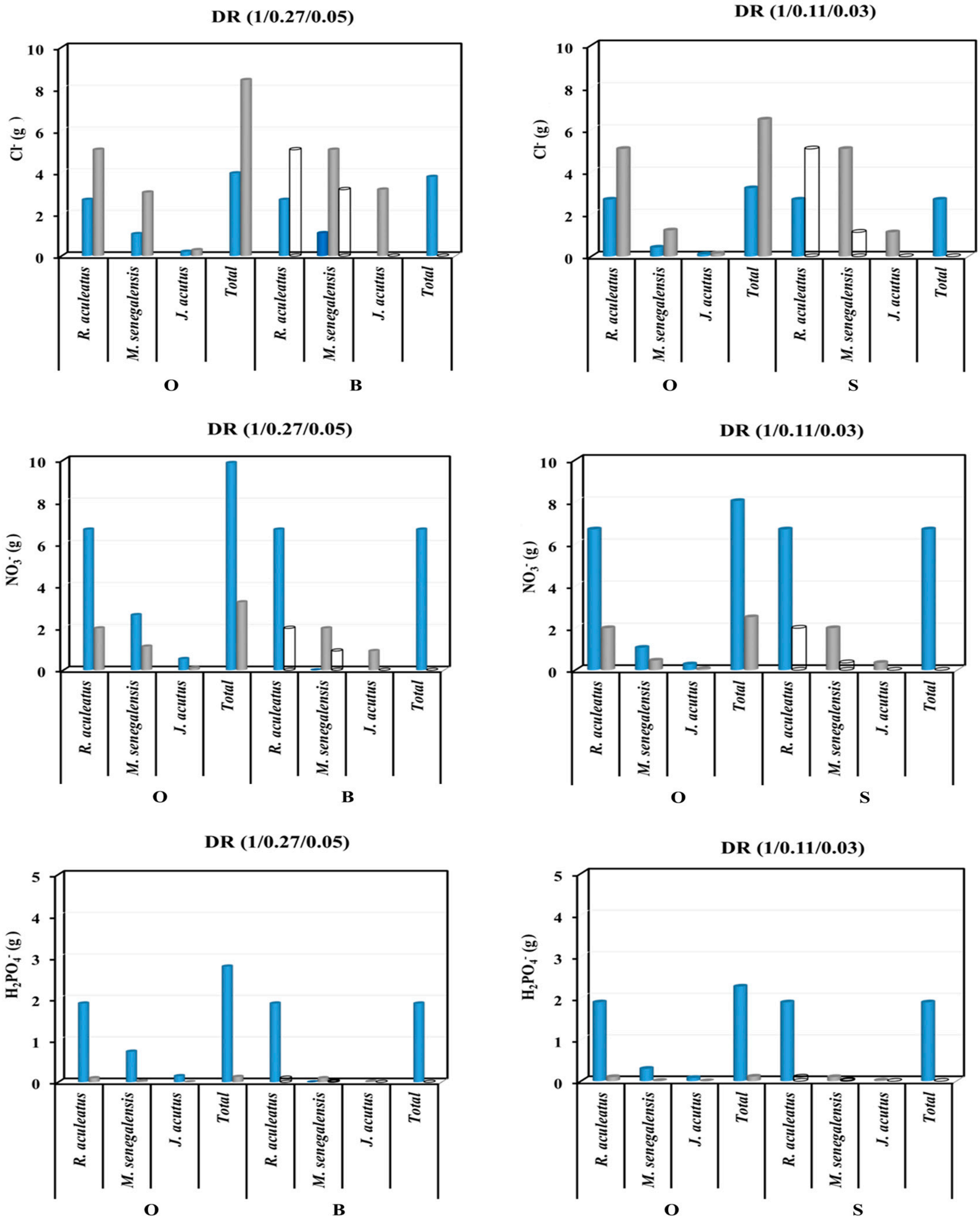

Figure 2. Water volume and anion loads of each water treatment for their respective distribution ratio itemized by species and the total (DR, distribution of the number of plants of the three species that can be grown in each water system). O—open system, B—blended water system, and S—sequential reuse water system.

The anion loads in the drainage water were also calculated; comparing B against O, there was a removal of 5% of Cl^- (O (3.97 g) and B (3.80 g)), 32% of NO_3^- (O (9.87 g) and B (6.70 g)) and 32% of $H_2PO_4^-$ (O (2.79 g) and B (1.90 g)), respectively and the generation of no pollution that in the case of O resulted in 8.44 g of Cl^-, 3.24 g of NO_3^- and 0.13 g of $H_2PO_4^-$. In the case of S compared to O, there was a removal of 15% of Cl^- (O (3.24 g) and S (2.70 g)), 17% of NO_3^- (O (8.05 g) and S (6.70 g)) and 17% of $H_2PO_4^-$ (O (2.28 g) and B (1.90 g)), respectively and the generation of no pollution that in the case of O resulted in 6.49 g of Cl^-, 2.52 g of NO_3^- and 0.11 g of $H_2PO_4^-$.

For the cation loads (Figure 3), comparing B against O, there was a removal of 10% of Na^+ (O (2.21 g) and B (2.00 g)), 32% of K^+ (O (3.68 g) and B (2.50 g)), 7% of Ca^{2+} (O (2.94 g) and B (2.70 g)) and 18% of Mg^{2+} (O (2.20 g) and B (1.80 g)), respectively and the generation of no pollution that in the case of O resulted in 6.13 g of Na^+, 1.49 g of K^+, 7.71 g of Ca^{2+} and 1.80 g of Mg^{2+}. In the case of S compared to O, there was a removal of 17% of Na^+ (O (1.80 g) and S (1.50 g)), 22% of K^+ (O (3.00 g) and S (2.50 g)), 17% of Ca^{2+} (O (2.40 g) and S (2.00 g)) and 18% of Mg^{2+} (O (1.80 g) and B (1.50 g)), respectively and the generation of no pollution that in the case of O resulted in 4.65 g of Na^+, 1.15 g of K^+, 5.95 g of Ca^{2+} and 1.39 g of Mg^{2+}.

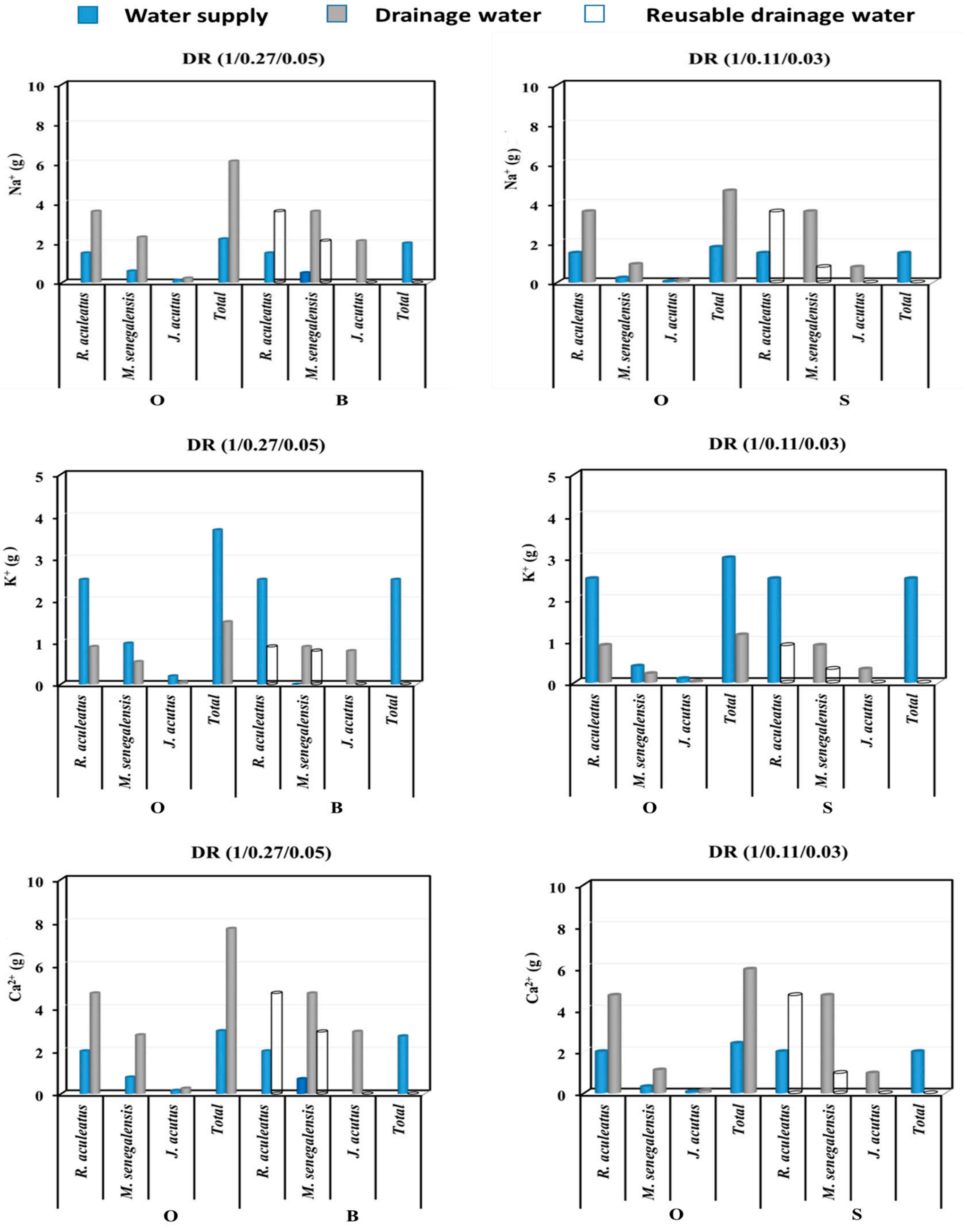

Figure 3. *Cont.*

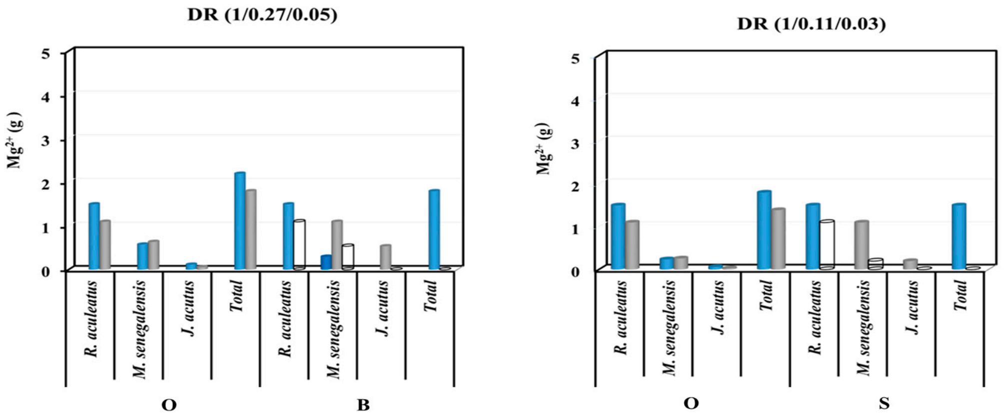

Figure 3. Cation loads of each water treatment for their respective distribution ratio itemized by species and the total (DR, distribution of the number plants of the three species that can be grown in each water system). O—open system, B—blended water system, and S—sequential reuse water system.

4. Discussion

The increase of EC in the drainage waters compared to the original nutrient solution could be due to the increase of Na^+, Cl^-, $SO_4{}^{2-}$, and Ca^{2+} concentrations caused primarily by the concentrating effects of plant water uptake, as reported by Massa et al. [5] and Glen et al. [20]. The reduction of $NO_3{}^-$ and $H_2PO_4{}^-$ concentrations in the waters applied for irrigation compared to the nutrient solution could be related to the plant water uptake that met nutritional needs as reported Broschat [21]. In the case of pH, the increase could be related to the alkalinity of the tap water due to high concentrations of bicarbonates [22].

The higher growth and biomass of *Ms* and *Ja* plants irrigated with closed systems (B and S) compared to O may be related to the increase of EC generated in B and S which resulted in a better growth of these species as reported by Schnoor et al. [23] and Green [24]. These results suggest the need for implementation of these kinds of closed systems between growers, but the reality is that their establishment is still incipient due to the high investment necessary. The selection of species with different degree of salt tolerance in our experiment, following the recommendations given by Hunt et al. [25] about plant selection for bioretention systems, could be another crucial factor. Similarly, Flowers and Colmer [26] reported that the growth of salt tolerant plants is improved under increasing saline conditions. Finally, it is noteworthy that even though there are many experiments about the effects of these types of water treatments on water and nutrient removal in the literature, our experiment is a new contribution since it also includes data on the effects of these water systems on the growth and biomass of the species, which are important from the grower's point of view.

The comparison between closed systems (B and S) with an open system (O) showed a reduction of the water volume and nutrient loads. The reduction of the water volume accomplished in these closed systems is a great advantage, particularly in areas with scarcity of water such as the Mediterranean area [27], and at the same time the absence of drainage indicates a higher sustainability, which is important for the environment. At the level of anion loads, higher removal of $NO_3{}^-$ and $H_2PO_4{}^-$ in these closed systems than in the open system may be due to the fact that the more intensive growth of these crops resulted in a higher uptake of N [28] and P [29]. The percentages of nutrient removal in these water systems were lower than in the other systems, such as the soil treatment [30,31] or biofiltration systems [32] where the percentages of nutrient removal were higher than 50%, pointing out that the results obtained in so different environmental conditions are not directly comparable. On the other hand, the high potassium removal could be due to the high nutrient requirements of these crops and the lower removal of Na^+, Ca^{2+} and Mg^{2+} compared to K^+ could be due to the antagonism between these cations under saline conditions as reported by Marschner [33]. Similar results were reported in an experiment aiming to study biofiltration systems carried out by Szota et al. [32].

5. Conclusions

The improved plant biomass in the closed systems (B and S) compared with the open system (O) is related to the increase in the electrical conductivity of the drainages. Higher crop biomass, and consequently higher nutrient uptake, were possible during sequential reuse water treatment, because plant species included in the experiment were previously selected according to their different degrees of salt tolerance. Closed systems (B and S) resulted in higher water saving and nutrient removal in comparison to the open system (O), which is essential from an environmental point of view. Our results suggest that growers should be encouraged to use the equations established in this experiment for the design and setting-up of such water treatments for horticultural and ornamental crops in areas where the scarcity of water is relevant.

Acknowledgments: The authors thank T. Flowers for his suggestions and English style corrections.

Author Contributions: The authors contributed equally to this work.

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

Abbreviations

The following abbreviations are used in this manuscript:

DR	Distribution ratio
DW	Dry weight
EC	Electrical conductivity
PAR	Photosynthetically active radiation
RH	Relative humidity

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