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Nitrogen, Phosphorus, and Potassium Requirements to Improve *Portulaca oleracea* L. Growth, Nutrient and Water Use Efficiency in Hydroponics

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Abstract: Purslane (*Portulaca oleracea* L.) is an herbaceous species that is traditionally consumed across the world due to its nutraceutical quality, boasting anticancer, anti-inflammatory and antidiabetic properties. These traits render purslane an attractive wild edible species for research and commercial exploitation. The current study examined the effect of different nitrogen (N) concentrations (100–200 mg L^{-1}; as N100, N200) in combination with different levels (decreased 0.66-fold: dec, recommended 1-fold: rec, or increased 1.5-fold: inc) of phosphorus (P; 47–70–105 mg L^{-1}) and potassium (K; 250–350–525 mg L^{-1}) in the nutrient solution (NS) used in hydroponic nutrient film technique (NFT) cultivation. The N200_PKinc NS resulted in improved crop growth compared to N200_PKrec NS, suggesting a positive correlation between optimal N levels (i.e., 200 mg L^{-1}) and increased P and K levels (105 and 525 mg L^{-1}, respectively). Plants grown in N200_PKinc revealed decreased antioxidant activity (e.g., DPPH, FRAP, and ABTS), phenols and flavonoids, while simultaneously increased total soluble solids levels. The recommended levels of P and K mirrored low levels in lipid peroxidation, mainly due to the increase in catalase enzymatic activity. Higher nutrient use efficiency was observed when both N100_PKinc and N200_PKinc were applied, resulting in higher yield and enhanced plant growth, while N100_PKinc produced plants with increased antioxidant activity. These findings suggest that both (N200_PKinc and N100_PKinc) NS have potential benefits for the hydroponic cultivation of purslane, with the latter NS offering additional advantages in terms of higher produce quality.

Keywords: antioxidants; mineral fertilizer; soilless culture; purslane; macronutrients

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1. Introduction

Purslane (*Portulaca oleracea* L.) is a widespread herbaceous species and member of the Portulacaceae family [1], and has been reviewed by Kumar et al. [2] as the eighth most commonly distributed plant in the world. While classified as an invasive weed in many regions, purslane is traditionally consumed across Europe, the Middle East, and Asia [3]. Recently, purslane has received increased attention due to its nutraceutical quality, possessing antidiabetic, anti-inflammatory, anticancer, antiarthritic, bactericidal, antiseptic and nephroprotective properties [4–6]. Phytochemical analysis has revealed that purslane is rich in ω-3 and ω-6 fatty acids, tocopherols, ascorbic acid, and specialized metabolites such as anthocyanins, flavonoids, and phenolic acids [7]. Furthermore, the plant is rich in dietary minerals such as nitrogen (N), potassium (K), magnesium (Mg), iron (Fe), zinc (Zn), boron (B), and copper (Cu) [1]. Because of its great plasticity, the species can tolerate a

variety of abiotic stress factors, including high salinity, droughts, and high temperatures, and it has a short growth cycle and has been established as a phytoremediation crop [1,4,8].

Commercial cultivation of the species has been established in recent decades, while it has also been introduced in intensive cultivation systems such as hydroponics [9,10], that offers significant advantages over traditional soil cultivation, including increased yields, and quality and reduced environmental impact [11]. This system enables precise nutrient management via the nutrient solution (NS) in a way to meet the nutritional needs of the cultivated crops, while the recirculation of this NS in closed hydroponic systems limits the discharge of nutrients in the ground water and results in fertilizer savings [12]. Furthermore, because hydroponics can guarantee a steady supply of plant material with high and consistent quality, as required by the industry and agricultural factor, it offers a viable method for growing wild edible and medicinal plants [13].

Optimizing crop nutrition in hydroponic systems necessitates the fine-tuning of the synthesis of the applied NS, to precisely meet the species-specific requirements [12]. Towards this end, customized NS formulations are implemented to ensure optimal growth, yield and quality. The critical role of macronutrients, and particularly N, P, and K on the various metabolic functions of plants, underscores the importance of tailor-made crop nutrition [14]. This is especially important for medicinal and wild edible plants, which often lack comprehensive nutritional data [15,16]. Nitrogen affects photosynthesis, metabolic processes, and crop output, among other aspects of plant growth and development [17,18]. However, excessive N application may be detrimental to the quality and post-harvest life of edible plant parts [19,20] as well as altering the balance of the vegetative to the reproductive phases during plant growth. In addition, imbalanced N supply may disrupt the balance of other essential nutrients. Given their interactions, N and P intake must be coordinated to provide the optimal nutritional balance. Furthermore, K uptake is interconnected with N uptake, because it is important in the metabolism of N, while the optimal N levels influence the efficacy of K fertilization [21,22]. Ultimately, sufficient levels of both P and K in the nutrient solution promote the accumulation of N and the increase in the N use efficiency, while N can affect the efficiency of P and K utilization [17,23].

Purslane has been the subject of extensive research interest due to its intrinsic characteristics, although information regarding its soilless cultivation under the influence of varying N, P and K concentrations in the NS is limited. Previous reports had determined the optimum level of N [4] and ammonium to total N ratios [24] in purslane, but no available data exist for the K and P levels in the NS under hydroponic culture conditions, which may affect the plant growth and nutrient profile of the selected species. Previous studies indicated the importance of the P and K levels as well as the N interaction with the former in several crops [23,25–28]. For purslane, the impacts of the K and P levels in the NS have not been studied previously. The goal of the current study was to determine how purslane's growth, physiology, antioxidant activity, nutrient accumulation and translocation, and water and nutrient use efficiency were affected by typical and elevated N levels in the NS, in combination with different levels of P and K. The selected nutrient levels were based on previously published data [4].

2. Materials and Methods

2.1. Cropping System, Plant Material and Growth Conditions

This study was conducted at the experimental farm of the Cyprus University of Technology, in Limassol, Cyprus, in a plastic multi-span greenhouse. The greenhouse is equipped with an automated climate control system (ventilation, shading, and cooling premises) and a hydroponic installation, constructed according to the principles of NFT (Nutrient Film Technique) as described previously [4]. Three hydroponic units (replicates)

were used for each treatment. Each unit consisted of a twin plastic channel set and was supported with an individual water replenishment tank. A density of 25 plants m^{-2} was achieved with the above constructions/hydroponic units, as each hydroponic unit accommodated 12 plants, as reported previously [4].

Two different N concentrations (100–200 mg L^{-1}; as N100, N200) were selected based on the increased yield, nutritional value and water use efficiency from previously published data [4]. The effect of the two N levels in combination with different levels [decreased 0.66-fold (times): dec, recommended 1-fold: rec, or increased 1.5-fold: inc] of phosphorus (P 47–70–105 mg L^{-1}) and potassium (K 250–350–525 mg L^{-1}) were examined. Mean daylight hours' air temperature, humidity and light intensity in the greenhouse were 24.1 °C, 56.6% and 1178 Lux, respectively, during the 30 days cultivation period.

Purslane (*P. oleracea* L., cv. Greek common purslane) seeds were purchased from a seed producer in Greece (Geniki Phytotechniki Athinon SA, Athens, Greece) and were sown in early spring (10 March 2022) in peat-perlite (85:15 *v*/*v*)-based growing media (Professional peat, Gebr. Brill Substrate GmbH & Co.KG, Georgsdorf, Germany) in black seedling trays, under nursery conditions. Seedlings at the stage of the first true leaf were then transplanted into netted pots (11 days after sowing) on 21 March 2022, filled with perlite and were placed in the recipients of the NFT channels, where they were supplemented with a standard (starter) NS (sNS) for 8 days to allow recovery from the transplanting stress.

The nutrient concentrations in the standard NS were as follows: NO_3^--N = 13.7, K^+ = 7.5, PO_4^{3-}-P = 1.8, Ca^{2+} = 3.5, Mg^{2+} = 1.0, SO_4^{2-}-S = 1.3 and Na^+ = 1.9 mmol L^{-1}, respectively; and B = 30.0, Fe = 30.0, Mn = 5.0, Cu = 1.0, Zn = 4.0, and Mo = 0.5 µmol L^{-1}, respectively. Following the 8-day of acclimation period in the NFT system, utilizing a standardized starter NS, on 29 March 2022 the plants were subjected to the different modified NS for 22 days (Table 1). The total cultivation period was 30 days (21 March to 19 April 2022) in the NFT system. Daily monitoring of the NSs was conducted, with adjustments made as necessary [28,29]. The NS absorbed by the plants was replenished from the replenishment tank automatically, and the adjustment of the electrical conductivity (EC) and pH were conducted daily by adding appropriate amounts of stock solutions of fertilizers. Sulfuric acid (H_2SO_4, 5% *v*/*v*) was used to decrease pH as needed, due to the alkalinity of the water used. The target pH and EC of the nutrient solution were 5.8 and 2.3 dS m^{-1}, respectively. All chemical reagents used for the plant tissue analysis were purchased from Sigma Aldrich (Steinheim, Germany) unless mentioned differently.

Table 1. Electrical conductivity (EC) and nutrient concentrations in the nutrient solution (NS) supplied to purslane plants grown in a closed hydroponic system. Nitrogen (N) concentration (100–200 mg L^{-1}; as N100, N200) combined with different levels (decreased 0.66-fold: dec, recommended 1-fold: rec, or increased 1.5-fold: inc) of phosphorus (P; 47–70–105 mg L^{-1}) and potassium (K; 250–350–525 mg L^{-1}) in the NS.

Parameters	sNS	N100_PKdec	N200_PKdec	N100_PKrec	N200_PKrec	N100_PKinc	N200_PKinc
EC dS m^{-1}	1.75	2.29	2.34	2.34	2.36	2.37	2.38
K^+ mmol L^{-1}	7.55	6.39	6.39	8.95	8.95	13.43	13.43
Ca^{2+} mmol L^{-1}	3.50	3.74	3.74	3.74	3.74	3.74	3.74
Mg^{2+} mmol L^{-1}	1.00	2.88	2.88	2.88	2.88	2.88	2.88
NH_4^+ mmol L^{-1}	0.5	0.42	0.83	0.42	0.83	0.42	0.83
NO_3^- mmol L^{-1}	13.72	6.73	13.46	6.73	13.46	6.73	13.46
SO_4^{2-} mmol L^{-1}	1.29	5.42	2.10	6.33	3.01	8.01	4.69
$H_2PO_4^-$ mmol L^{-1}	1.80	1.52	1.52	2.26	2.26	3.39	3.39
Cl^- mmol L^{-1}	1.49	1.49	1.49	1.49	1.49	1.49	1.49
Fe µmol L^{-1}	30.00	71.56	71.56	71.56	71.56	71.56	71.56
Mn µmol L^{-1}	5.00	18.21	18.21	18.21	18.21	18.21	18.21
Zn µmol L^{-1}	4.00	1.53	1.53	1.53	1.53	1.53	1.53

Table 1. *Cont.*

Parameters	sNS	N100_PKdec	N200_PKdec	N100_PKrec	N200_PKrec	N100_PKinc	N200_PKinc
Cu μmol L^{-1}	1.00	4.72	4.72	4.72	4.72	4.72	4.72
B μmol L^{-1}	30.00	18.52	18.52	18.52	18.52	18.52	18.52
Mo μmol L^{-1}	0.50	0.52	0.52	0.52	0.52	0.52	0.52

The starter nutrient solution (sNS) was used for 8 days, before the application of the modified NS as (1) N100_PKdec, (2) N200_PKdec, (3) N100_PKrec, (4) N200_PKrec, (5) N100_PKinc, and (6) N200_PKinc.

2.2. Plant Measurements and Sampling

A total of 216 plants were used for the evaluation of the tested nutrient solutions. Following 22 days of plant growth, six individual plants (from different replication units) of each treatment were sampled. Various plant growth-related measurements were implemented, including plant height (cm), leaf number, above plant biomass (stems and leaves) fresh weight (g), and dry weight (g) as well as root fresh weight (g), and dry weight (g). The percentage of dry matter content was also calculated.

2.3. Plant Physiological and Photosynthetic-Related Parameters

Leaf stomatal conductance was measured with a Delta-T AP4 porometer (Delta-T Devices-Cambridge, UK) and expressed as mmol H_2O m^{-2} s^{-1}. The relative chlorophyll content was assessed using an optical chlorophyll meter (SPAD-502, Minolta, Osaka, Japan). Leaf chlorophyll fluorescence of PSII (Fv/Fm) was measured using a Chlorophyll Fluorometer (OptiSci OS-30p, Opti-Sciences, Hertfordshire, UK). Additionally, fresh plant tissue (six replications/treatment; 0.1 g) was used for chlorophyll extraction. Photosynthetic leaf pigments, chlorophyll a (Chl a), chlorophyll b (Chl b), total chlorophyll (total Chl) and carotenoids (Car) content were then calculated (mg g^{-1} fresh weight-FW) by following the methodology reported previously [30,31].

2.4. Plant Tissue and Nutrient Ion Concentration Analysis

At the end of the experiment, samples from leaves, stems and roots were used to determine the mineral content in six replications per treatment. Plant tissue was dried to constant weight (at 65 °C for 4 days), was ash-burned at 450 °C for 6 hours and then acid digested (2 M HCl). Determination of K, Na, and P content was performed according to Chrysargyris et al. [29] while Mg and calcium (Ca) were determined by an atomic absorption spectrophotometer (PG Instruments AA500FG, Leicestershire, UK). Nitrogen was determined by the Kjeldahl method (BUCHI, Digest automat K-439 and Distillation Kjeldahl K-360, Flawil, Switzerland). Data were expressed in g kg^{-1} of dry weight.

The total amount of water used by the plants during the cropping period was recorded and water uptake (mL $plant^{-1}$ day^{-1}) was calculated. The water and nutrient uptakes were calculated per hydroponic channel-unit and then divided by the number of plants that were grown in the channels. The calculated value was divided for the duration of the cropping period. The total amount of nutrients used by the plants was recorded from the stock solutions in the NS and the nutrients that remained at the drainage solution were subtracted at the end of the cropping period.

Water use efficiency (WUE) was calculated by the ratio between the biomass produced by a crop and the water consumed, as described as follows:

$$\text{WUE} = \frac{\text{Biomass (g per plant)}}{\text{Water (L per plant)}} \quad (1)$$

The nutrient use efficiency (NUE) was calculated by the ratio of biomass to volume of the NS supply, as described as follows:

$$\text{NUE} = \frac{\text{Biomass (g per plant)}}{\text{NS (mL per plant)}} \quad (2)$$

2.5. Total Phenolics, Total Flavonoids, Antioxidant Activity, Ascorbic Acid and Total Soluble Solids

Polyphenols were extracted from six samples for each treatment. Methanolic extracts of the plant tissue (0.7 g) were stored at −20 °C until analysis of total phenolic and flavonoids content. The total antioxidant activity was assessed by the 2,2-diphenyl-1-picrylhydrazyl (DPPH), the ferric reducing antioxidant power (FRAP) and the 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid (ABTS) methods.

The total phenolic content measurement was performed with the Folin–Ciocalteu method (at 755 nm) as described previously [24]. Results were expressed in gallic acid equivalents (mg GA g^{-1} FW). The content of total flavonoids was determined using the aluminum chloride colorimetric method [32] as modified in Chrysargyris et al. [33]. The absorbance was measured at 510 nm. The total flavonoid content was expressed as rutin equivalents (mg rutin g^{-1} FW).

Free radical-scavenging activity was determined as described previously [34]. Briefly, the DPPH radical scavenging activity of the leaf extracts was measured at 517 nm while the FRAP activity was measured at 593 nm, as described in Chrysargyris et al. [34]. The ABTS assay was implemented according to the methodology described by Woidjylo et al. [35]. Results were expressed as Trolox ((±)-6-Hydroxy-2,5,7,8-tetramethylchromane-2-carboxylic acid) equivalents (mg trolox g^{-1} of fresh weight).

Ascorbic acid (AA) was determined by the 2,6-Dichloroindophenol titrimetric method as described previously [36]. Plant tissue (0.5 g) was extracted in 10 mL oxalic acid 4.0% and was titrated by the dye solution until the color changed. Data were expressed as μg of AA per gram of fresh weight.

The total soluble solids (TSS) content was determined from the juice obtained from plant tissue with a temperature-compensated digital refractometer (model Sper Scientific 300017, Scottsdale, AZ, USA) at 20 °C, and results were expressed in percentage (%).

2.6. Lipid Peroxidation, Hydrogen Peroxide, and Enzymes Antioxidant Activity

The content of hydrogen peroxide (H_2O_2) was determined by the method described by Loreto and Velikova [37]. Six samples were used for this analysis from each treatment. The H_2O_2 content was measured using standards of 5 to 1000 μM of H_2O_2 and the calibration curve was plotted accordingly. Samples and standards were measured at 390 nm and the results were expressed as μmol H_2O_2 g^{-1} fresh weight.

Lipid peroxidation, in terms of malondialdehyde content (MDA), was assessed according to De Azevedo Neto et al. [38]. The absorbance was recorded at 532 nm and corrected for non-specific absorbance at 600 nm. MDA content was determined using the extinction coefficient of 155 mM cm^{-1}. Results were expressed as nmol of MDA g^{-1} fresh weight.

The activity of the antioxidant enzymes for superoxide dismutase (SOD) (EC 1.15.1.1) and for catalase (CAT) (EC 1.11.1.6) was assayed as described previously [29] and the absorbance was determined at 560 nm for SOD and at 240 nm for CAT. Peroxidase activity (POD) (EC 1.11.1.6) was determined following the increase in absorbance at 430 nm as described previously [28]. Results were expressed as enzyme units per mg of protein. The protein content in leaf tissue was measured using the Bradford method and bovine serum albumin as a standard.

2.7. Statistical Methods

Analysis of variance (ANOVA) on data was performed by IBM SPSS v.22, and results from six replicates per treatment were presented as treatment mean ± standard error (SE).

Duncan's multiple range tests were performed when the ANOVA rendered a significant treatment impact at $p < 0.05$.

3. Results

3.1. The Evolution of Nutrient Solution EC and pH

The evolution of the EC and pH of the drainage NSs of each treatment is presented in Figure S1 of the supplementary file. In general, the pH and the EC of the drainage NSs in the NFT system did not differ among treatments. During the initial 8-day period, the EC fluctuated from 1.5 to 2.0 dS m^{-1}, while following the introduction of the modified nutrient solutions, the EC reached the target value of 2.3 dS m^{-1}. The target value of pH was set at 5.8 and fluctuated from 5.5 to 6.5 during the course of the experiment (Figure S1).

3.2. Plant Growth and Physiology

Purslane plants grown with N200_PKinc presented increased height (25.9%), above-ground plant fresh weight (69.0%), and leaf fresh weight (50.9%) compared to plants grown with N200_PKrec. Additionally, plants grown with N200_PKinc exhibited increased stem fresh weight of up to 98.0%, compared to plants grown with N200_PKrec. Finally, fertilization with N100_PKinc increased the number of leaves produced, as well as the leaf dry weight, compared to N200_PKrec (Table 2).

Table 2. Effect of nitrogen (N) concentration (100–200 mg L^{-1}; as N100, N200) in combination with different levels (decreased 0.66-fold: dec, recommended 1-fold: rec, or increased 1.5-fold: inc) of phosphorus (P; 47–70–105 mg L^{-1}) and potassium (K; 250–350–525 mg L^{-1}) on plant height (cm), number of leaves, above-ground plant (leaves and stems) and roots fresh weight (g; FW), dry weight (g; DW) and dry matter content (%; DM) of purslane plants grown hydroponically in the NFT system.

N-P-K	Above-ground plant FW	Leaf FW	Stem FW	Plant height	Number of leaves	
N100_PKdec	80.70 ± 9.27 ab	47.50 ± 4.60 ab	31.93 ± 4.23 abc	25.33 ± 2.46 ab	114 ± 15.0 ab	
N200_PKdec	62.97 ± 8.91 ab	37.86 ± 4.16 ab	23.46 ± 4.74 bc	23.33 ± 1.20 ab	87.3 ± 12.3 ab	
N100_PKrec	61.73 ± 6.58 ab	37.13 ± 3.54 ab	23.46 ± 3.06 bc	23.67 ± 0.88 ab	86.0 ± 7.51 ab	
N200_PKrec	54.20 ± 9.96 b	33.70 ± 6.46 b	19.76 ± 3.70 c	22.50 ± 1.00 b	80.3 ± 7.84 b	
N100_PKinc	79.70 ± 9.38 ab	43.33 ± 4.41 ab	34.56 ± 4.84 ab	27.17 ± 1.17 ab	125 ± 17.30 a	
N200_PKinc	91.60 ± 9.25 a	50.86 ± 3.64 a	39.13 ± 5.18 a	28.33 ± 1.64 a	108 ± 9.82 ab	
N-P-K	Above-ground plant DW	Leaf DW	Stem DW	Above-ground plant DM	Leaf DM	Stem DM
N100_PKdec	3.08 ± 0.43	1.76 ± 0.14 ab	1.31 ± 0.28	3.79 ± 0.10 ab	3.73 ± 0.07 b	4.01 ± 0.32
N200_PKdec	2.40 ± 0.40	1.47 ± 0.16 ab	0.92 ± 0.23	3.78 ± 0.13 ab	3.88 ± 0.03 ab	3.88 ± 0.26
N100_PKrec	2.17 ± 0.27	1.29 ± 0.15 ab	0.87 ± 0.11	3.51 ± 0.17 ab	3.48 ± 0.25 b	3.73 ± 0.08
N200_PKrec	2.11 ± 0.45	1.25 ± 0.20 b	0.86 ± 0.24	3.88 ± 0.17 ab	3.77 ± 0.16 b	4.24 ± 0.47
N100_PKinc	3.15 ± 0.42	1.85 ± 0.22 a	1.30 ± 0.20	3.94 ± 0.11 a	4.25 ± 0.11 a	3.74 ± 0.09
N200_PKinc	3.14 ± 0.25	1.75 ± 0.08 ab	1.38 ± 0.17	3.44 ± 0.09 b	3.46 ± 0.10 b	3.54 ± 0.06

Significant differences ($p < 0.05$) among modified NS are indicated by different letters.

The different modified nutrient solutions affected purslane plant physiology as plants grown with N200_PKdec had increased stomatal conductance (up to 59.2%), compared to plants grown with all other nutrient solutions, excluding the application of N200_PKrec, which did not differ significantly. Additionally, the application of N200_PKrec resulted in plants with the highest chlorophyll content (chlorophyll a, b and total chlorophylls), exhibiting a 54.2, 66.7, and 53.4% increase, respectively, compared to the N200_PKdec treatment which produced plants with overall lower chlorophyll content (Table 3). Total carotenoids content and chlorophyll fluorescence did not differ in plants among the examined treatments.

Table 3. Effect of nitrogen (N) concentration (100–200 mg L^{-1}; as N100, N200) in combination with different levels (decreased 0.66-fold: dec, recommended 1-fold: rec, or increased 1.5-fold: inc) of phosphorus (P; 47–70–105 mg L^{-1}) and potassium (K; 250–350–525 mg L^{-1}) on leaf stomatal conductance (mmol m^{-2} s^{-1}), SPAD value, leaf chlorophyll fluorescence (Fv/Fm), chlorophyll content (a, b, total; mg g^{-1} fresh weight) and carotenoids (mg g^{-1} fresh weight) of purslane plants grown hydroponically in the NFT system.

N-P-K	Stomatal Conductance	SPAD	Chlorophyll Fluorescence	Chlorophyll a	Chlorophyll b	Total Chlorophylls	Carotenoids
N100_PKdec	66.60 ± 10.41 b	30.38 ± 1.77	0.72 ± 0.02	0.34 ± 0.05 ab	0.10 ± 0.01 ab	0.43 ± 0.06 ab	0.06 ± 0.01
N200_PKdec	106.00 ± 8.28 a	28.88 ± 0.89	0.71 ± 0.05	0.24 ± 0.02 b	0.06 ± 0.004 b	0.30 ± 0.02 b	0.05 ± 0.004
N100_PKrec	76.60 ± 5.57 b	32.45 ± 1.58	0.75 ± 0.01	0.27 ± 0.03 ab	0.08 ± 0.004 ab	0.35 ± 0.04 ab	0.06 ± 0.01
N200_PKrec	88.40 ± 5.66 ab	30.50 ± 0.84	0.70 ± 0.02	0.37 ± 0.04 a	0.10 ± 0.01 a	0.46 ± 0.06 a	0.07 ± 0.01
N100_PKinc	75.80 ± 1.96 b	30.90 ± 1.69	0.72 ± 0.02	0.31 ± 0.02 ab	0.08 ± 0.004 ab	0.38 ± 0.02 ab	0.06 ± 0.004
N200_PKinc	69.70 ± 6.59 b	28.05 ± 1.28	0.72 ± 0.02	0.28 ± 0.04 ab	0.07 ± 0.01 ab	0.35 ± 0.05 ab	0.06 ± 0.01

Significant differences ($p < 0.05$) among modified NS are indicated by different letters.

3.3. Plant Mineral Status

Purslane leaf, stem and root nutrient content is presented in Table 4. Increased levels of N were measured in the leaves of plants grown with N100_PKinc, compared to leaves of plants grown with N100_PKdec, N200_PKinc, N100_PKrec, and N200_PKrec. The same nutrient solution also produced plants with increased Ca and Mg levels in leaves, compared to all the other tested treatments. Plants grown with N200_PKinc revealed the highest leaf K and P content compared to the other treatments. Finally, leaf Na content was the highest with the application of N200_PKdec, while N100_PKrec produced plants with the lowest leaf Na content.

Table 4. Effect of nitrogen (N) concentration (100–200 mg L^{-1}; as N100, N200) in combination with different levels (decreased 0.66-fold: dec, recommended 1-fold: rec, or increased 1.5-fold: inc) of phosphorus (P; 47–70–105 mg L^{-1}) and potassium (K; 250–350–525 mg L^{-1}) in the nutrient solution on the content (g kg^{-1}) of macronutrients in leaves, stems and roots of purslane plants grown hydroponically in the NFT system.

Leaves						
N-P-K	N	K	P	Ca	Mg	Na
N100_PKdec	51.41 ± 0.45 c	109.19 ± 1.92 c	14.16 ± 0.41 b	9.26 ± 0.16 c	13.65 ± 0.30 bc	5.54 ± 0.15 b
N200_PKdec	53.96 ± 0.86 ab	115.79 ± 0.97 b	12.46 ± 0.21 c	10.83 ± 0.14 b	14.10 ± 0.17 b	6.10 ± 0.06 a
N100_PKrec	52.33 ± 0.79 bc	109.67 ± 4.84 c	12.98 ± 0.28 bc	6.77 ± 0.39 d	9.06 ± 0.53 e	3.91 ± 0.37 c
N200_PKrec	52.30 ± 0.52 bc	115.89 ± 1.00 b	12.50 ± 0.30 c	9.38 ± 0.11 c	11.10 ± 0.10 d	5.48 ± 0.27 b
N100_PKinc	54.98 ± 0.63 a	70.05 ± 0.41 d	12.95 ± 0.55 bc	17.64 ± 0.05 a	22.33 ± 0.05 a	5.49 ± 0.07 b
N200_PKinc	50.72 ± 0.57 c	124.16 ± 1.96 a	15.79 ± 0.42 a	8.97 ± 0.25 c	13.01 ± 0.26 c	5.35 ± 0.10 b
Stems						
N-P-K	N	K	P	Ca	Mg	Na
N100_PKdec	39.34 ± 1.68 bc	126.20 ± 4.73 c	7.39 ± 0.39 a	2.00 ± 0.09 b	5.64 ± 0.24 b	4.77 ± 0.17 b
N200_PKdec	40.37 ± 0.67 abc	138.71 ± 2.94 b	6.76 ± 0.56 a	2.77 ± 0.19 b	5.56 ± 0.31 b	4.24 ± 0.19 bc
N100_PKrec	41.80 ± 0.70 ab	149.02 ± 3.29 a	7.57 ± 0.04 a	1.95 ± 0.14 d	3.10 ± 0.19 d	1.54 ± 0.12 e
N200_PKrec	43.23 ± 0.84 a	130.64 ± 2.35 bc	7.17 ± 0.18 a	2.52 ± 0.11 c	4.73 ± 0.16 c	2.66 ± 0.06 d
N100_PKinc	37.57 ± 0.98 cd	91.67 ± 1.51 d	5.45 ± 0.08 b	3.82 ± 0.12 a	10.84 ± 0.06 a	10.61 ± 0.39 a
N200_PKinc	35.27 ± 0.81 d	126.44 ± 3.06 c	7.77 ± 0.22 a	1.55 ± 0.04 d	3.62 ± 0.15 d	3.59 ± 0.35 c
Roots						
N-P-K	N	K	P	Ca	Mg	Na
N100_PKdec	41.46 ± 0.48 de	11.93 ± 0.16 d	10.20 ± 0.07	5.49 ± 0.05 c	9.04 ± 0.13 d	11.52 ± 0.02 a
N200_PKdec	45.16 ± 0.63 b	12.00 ± 0.12 d	10.83 ± 0.11	5.74 ± 0.06 b	12.17 ± 0.12 a	11.74 ± 0.12 a
N100_PKrec	40.07 ± 0.56 e	32.42 ± 2.18 a	10.16 ± 0.25	5.84 ± 0.04 ab	9.43 ± 0.48 cd	4.86 ± 0.59 c
N200_PKrec	42.37 ± 0.42 cd	21.62 ± 0.21 b	11.11 ± 0.11	6.04 ± 0.06 a	11.06 ± 0.11 b	8.14 ± 0.08 b
N100_PKinc	48.54 ± 0.09 a	14.90 ± 0.58 cd	10.06 ± 0.49	5.44 ± 0.08 c	10.19 ± 0.46 bc	10.97 ± 0.73 a
N200_PKinc	43.08 ± 0.19 c	17.19 ± 0.46 c	11.10 ± 0.82	5.97 ± 0.10 ab	9.60 ± 0.26 cd	8.63 ± 0.55 b

Nitrogen—N, Potassium—K, Phosphorus—P, Calcium—Ca, Magnesium—Mg, and Sodium—Na. Significant differences ($p < 0.05$) among modified NS are indicated by different letters.

Regarding plant stems, N content was the highest with the application of N200_PKrec, while it was the lowest with the application of N200_PKinc. The N100_PKrec application had significantly increased the stem K content of purslane plants, while the lowest stem K content was observed with the application of N100_PKinc as similarly observed with the K content of leaves. Furthermore, the application of N100_PKinc also negatively influenced the P accumulation in stems compared to the other treatments. However, the stems of plants grown with N100_PKinc had the highest Ca, Mg and Na content, attaining an increase of up to 146.5%, 249.7%, and 589%, respectively.

As similarly observed in leaves, the N100_PKinc application increased the root N content, contrary to the results obtained for the plant stems. The lowest root N content was observed in plants treated with N100_PKrec, while the application of this nutrient solution positively influenced the K content in roots, achieving an increase of 171.7%, compared to the lowest root K content which was observed with the application of N100_PKdec. Furthermore, root Ca content was the highest with the application of N200_PKrec, while the lowest were with N100_PKdec and N100_PKinc. Furthermore, the root Mg content was positively corelated with the application of N200_PKdec, while Na content was significantly decreased with the use of N100_PKrec. Finally, the P content did not differ in roots between the examined treatments.

The application of the modified nutrient solutions generally did not affect the nutrients and water uptake. Considering the nutrient use efficiency, it was affected by the P and K concentrations used, as indicated by the increase observed with the use of N100_PKinc and N200_PKinc, while the lowest NUE was observed at N100_PKrec, N200_PKrec and N200_PKdec. Finally, the water use efficiency was increased with the application of N100_PKinc, while N100_PKrec, N200_PKrec and N200_PKdec resulted in decreased WUE (Table 5).

Table 5. Effect of nitrogen (N) concentration (100–200 mg L^{-1}; as N100, N200) in combination with different levels (decreased 0.66-fold: dec, recommended 1-fold: rec, or increased 1.5-fold: inc) of phosphorus (P; 47–70–105 mg L^{-1}) and potassium (K; 250–350–525 mg L^{-1}) in the nutrient solution on the nutrients uptake (mL $plant^{-1}$), water uptake (mL $plant^{-1}$), nutrient use efficiency (NUE) (g DW mL^{-1} NS) and water use efficiency (WUE) (g DW mL^{-1} H_2O) of purslane plants grown hydroponically in the NFT system.

N-P-K	Nutrients Uptake	Water Uptake	NUE	WUE
N100_PKdec	15.95 ± 1.65	5.25 ± 0.08	0.19 ± 0.02 ab	0.58 ± 0.01 ab
N200_PKdec	14.29 ± 0.00	5.44 ± 0.71	0.16 ± 0.00 bc	0.44 ± 0.05 c
N100_PKrec	14.29 ± 0.00	4.57 ± 0.25	0.15 ± 0.00 c	0.47 ± 0.02 bc
N200_PKrec	14.29 ± 0.00	5.11 ± 0.57	0.14 ± 0.00 c	0.41 ± 0.04 c
N100_PKinc	14.29 ± 0.00	5.10 ± 0.27	0.22 ± 0.00 a	0.61 ± 0.03 a
N200_PKinc	14.29 ± 0.00	5.32 ± 0.23	0.22 ± 0.00 a	0.59 ± 0.02 ab

Significant differences ($p < 0.05$) among different NSs are indicated by different letters. DW: dry weight; NS: nutrient solution.

3.4. Antioxidant Activity, Total Phenols Content and Flavonoids

The impacts on total phenols content, flavonoids and antioxidant capacity of purslane plants are presented in Figure 1. Total phenolics were increased with the use of N100_PKinc, compared to N100_PKrec and N200_PKinc (Figure 1A). Similarly, the flavonoids (Figure 1B) and the antioxidant capacity (assayed by DPPH and FRAP) (Figure 1C, 1D) of purslane plants were decreased with the application of N100_PKrec and N200_PKinc, as opposed to the application of N200_PKrec and N100_PKinc, which also yielded the highest ABTS (Figure 1E), FRAP (Figure 1D) and DPPH (Figure 1C).

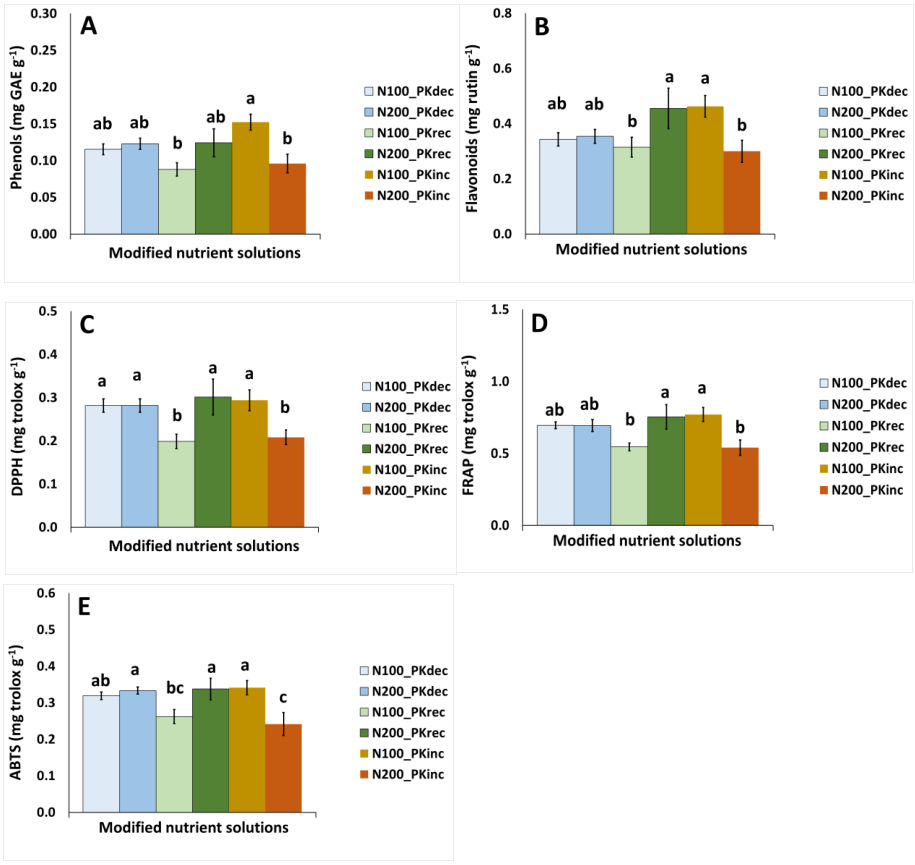

Figure 1. Effect of nitrogen (N) concentration (100–200 mg L^{-1}; as N100, N200) in combination with different levels (decreased 0.66-fold: dec, recommended 1-fold: rec, or increased 1.5-fold: inc) of phosphorus (P; 47–70–105 mg L^{-1}) and potassium (K; 250–350–525 mg L^{-1}) on (**A**) total phenols (mg GA g^{-1} fresh weight-FW), (**B**) flavonoids (mg Rutin g^{-1} FW), and (**C**–**E**) antioxidant activity (DPPH, FRAP, ABTS; mg Trolox g^{-1} FW) of purslane plants grown hydroponically in the NFT system. Significant differences ($p < 0.05$) among modified NS are indicated by different letters.

3.5. Total Soluble Solids and Ascorbic Acid Content

The effects on TSS and ascorbic acid of purslane plants are presented in Figure 2. TSS was increased with the use of N200_PKinc, while, interestingly, the lowest TSS percentage was observed with the decrease in N concentration (N100_PKinc) (Figure 2A). Furthermore, the ascorbic acid content was positively correlated with the application of N200_PKrec, while both N100_PKdec and N200_PKdec produced plants with the lowest ascorbic acid content (Figure 2B).

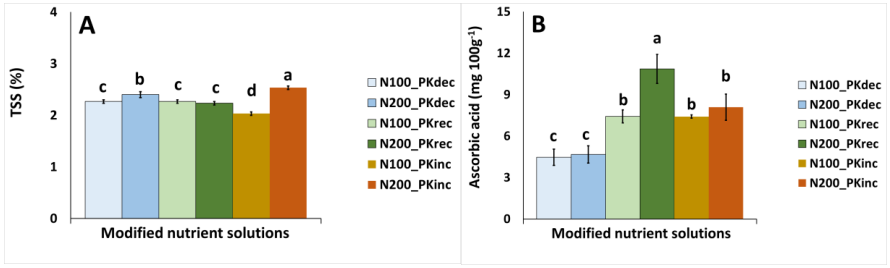

Figure 2. Effect of nitrogen (N) concentration (100–200 mg L^{-1}; as N100, N200) in combination (decreased 0.66-fold: dec, recommended 1-fold: rec, or increased 1.5-fold: inc) with phosphorus (P; 47–7–105 mg L^{-1}) and potassium (K; 250–350–525 mg L^{-1}) on (**A**) total soluble solids (TSS: %) and (**B**) ascorbic acid (mg 100 g^{-1} FW) of purslane plants grown hydroponically in the NFT system. Significant differences ($p < 0.05$) among modified NS are indicated by different letters.

3.6. Damage Indicators and Antioxidant Enzyme Activities

The effects on hydrogen peroxide (H_2O_2), lipid peroxidation (MDA) and antioxidant enzymes activity (SOD, CAT, and POD) are presented in Figure 3. In general, no differences were found in the H_2O_2 content (Figure 3A) and SOD activity (Figure 3C) of plants subjected to the modified NSs. In the case of MDA, a significant increase was observed with the application of N200_PKinc compared to N200_PKdec, N100_PKrec, and N200_PKrec, with the lowest lipid peroxidation being exhibited by plants grown under N200_PKrec (Figure 3B). Furthermore, CAT activity was generally higher with the application of both N100_PKrec and N200_PKrec which shared the same P and K concentrations in the NS, while the lowest was recorded with the application of N100_PKinc (Figure 3D). Finally, POD activity significantly increased with the application of N100_PKdec, while treatments N100_PKrec, N200_PKrec, N100_PKinc and N200_PKinc resulted in the lowest levels of POD activity (Figure 3E).

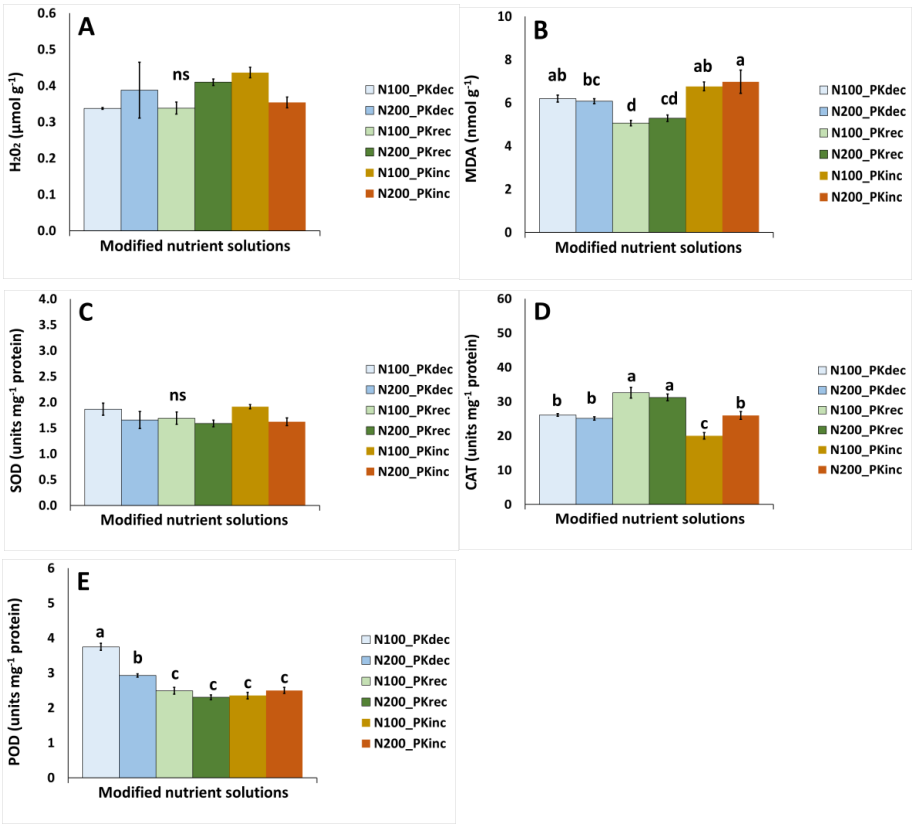

Figure 3. Effect of nitrogen (N) concentration (100–200 mg L^{-1}; as N100, N200) in combination with different levels (decreased 0.66-fold: dec, recommended 1-fold: rec, or increased 1.5-fold: inc) of phosphorus (P; 47–70–105 mg L^{-1}) and potassium (K; 250–350–525 mg L^{-1}) on (**A**) hydrogen peroxide— H_2O_2 (µmol g^{-1}), (**B**) lipid peroxidation-MDA (nmol g^{-1}) and antioxidant enzymes activity of (**C**) superoxide dismutase (SOD; units mg^{-1} protein), (**D**) catalase (CAT; units mg^{-1} protein), and (**E**) peroxidase (POD; units mg^{-1} protein) of purslane plants grown hydroponically in the NFT system. Significant differences ($p < 0.05$) among modified NS are indicated by different letters; ns indicates no significant differences.

4. Discussion

With its ability to provide exceptional control over plant nutrition through the use of a nutrient solution, hydroponics offers a potential method for growing specialty crops with consistent and high quality. However, information regarding the optimal nutrition of such crops in hydroponics is relatively scarce [11]. Studies on the hydroponic cultivation of

purslane have highlighted the critical role of balanced N levels in the NS [4] as well as the importance of ammonium to total N ratio in the NS [24]. In general, purslane exhibits low fertilization needs in soil, achieving optimal biomass production with 60 kg N ha^{-1} [39]. In hydroponics, decreased or elevated N levels (i.e., 50 and 300 mg L^{-1}, respectively) in the NS caused reduced purslane biomass production, accompanied by increased oxidative stress. Indeed, the intermediate N levels (i.e., 100-200 mg L^{-1}) showed decreased oxidative stress, and the best overall performance in hydroponic purslane production [4]. However, this study used standardized P and K levels, at 70 mg L^{-1} and 350 mg L^{-1}, respectively. Thus, the current study applied the optimal N levels (100 and 200 mg L^{-1}) of the previous reports [4], and three different P and K levels (decreased 0.66-fold, recommended 1-fold, or increased 1.5-fold) to determine the optimal N, P, and K rates in the hydroponic cultivation of purslane.

Effective nutrient management is critical for achieving high crop production. Parameters such as the fresh and dry plant weight are vital, as to ensure the economic viability of specialty crops such as purslane [40]. In hydroponics, the use of a half dose NS (with 50% reduced macronutrients) in baby-leaf purslane cultivated in a floating system, resulted in decreased yield, compared to using a full-dose NS [41], indicating nutrient shortage for the plant needs. Thus, providing balanced and tailor-made nutrition is crucial for achieving optimal growth, particularly in intensive cultivation applications. In the current study, the application of N200_PKinc NS resulted in improved above-ground FW, leaf FW and plant height, compared to using the N200_PKrec NS. The impact of N is less pronounced, as the two N levels examined (100 and 200 mg L^{-1}) were optimal for the cultivation of purslane [4]. These findings suggest a positive correlation between the application of increased levels of P and K, and enhanced growth parameters. This observation aligns with the well-established roles of P in photosynthesis and in enhancing various morphological traits, and K in cell division, expansion, and turgor [42,43]. Similar findings were observed by Salama et al. [44], as purslane growth-related indices (leaf FW, leaf area, leaf no, etc.) were improved with the increased level of P application, under field cultivation. Interestingly, in a P-competition study with lettuce and purslane, increasing P concentrations (up to 160 mg L^{-1}) in the NS did not affect the produced biomass of purslane, although it deprived lettuce of P [45]. These results, however, are not directly applicable, due to the presence of multiple plant species competing for the same nutrient pool. In addition, El-Sherbeny et al. [46] studied the effects of different NPK ratios on purslane plant growth, cultivated in field conditions, with the ratio of 200:100:50 providing optimum plant growth parameters (plant height, FW, DW, etc.). The differences that were observed in the examined studies, however, may be attributed to differences in harvesting time, the number of harvests as well as the soil buffering capacity that affect the minerals release and availability in roots [5]. In oil palm (*Elaeis guineensis* Jacq) hydroponic seedling production, the application of decreased P levels (15 mg L^{-1}) caused deficiency symptoms such as reduced biomass production and leaf expansion, as processes of the carbohydrate metabolism, including photosynthesis and respiration were negatively impacted. The reduction of K levels (50 mg L^{-1}) resulted in a decrease in both leaf area and plant dry weight, while a similar trend was observed with increased K levels (600 and 900 mg L^{-1}) [47]. However, the current study did not reveal the same outcomes, as the P and K levels applied were not exceptionally low or high. Furthermore, this aligns with purslane's low fertilizer input demands to obtain high yields [5].

Fertilization is closely related with the production of chlorophylls, impacting photosynthesis [48]. Nitrogen, as a participle in chlorophyll molecule structure, is expected to affect the chlorophyll content in leaves [49]. In addition, low P supply can result in chloroplast ultrastructure disorders, while a low K supply can accelerate the degrada-

tion of chloroplasts and inhibit chlorophyll fluorescence properties [23]. In the current study, chlorophylls (a, b, total) were positively affected by the recommended levels of P and K (1-fold; 70 and 350 mg L^{-1}, respectively), compared to decreased levels (0.66-fold; 47 and 250 mg L^{-1}, respectively), under the application of 200 mg N L^{-1}, which produced plants with the lowest chlorophyll contents. This may be attributed to the different K levels, which affected the N:K ratio; from 1:1.75 (N:K) at 350 mg L^{-1} K and 200 mg L^{-1} N, to 1:1.25 (N:K) at 250 mg L^{-1} K and 200 mg L^{-1} N. Maintaining a proper N:K ratio is important to improve leaf photosynthetic activity, which varies from 1.5 to 2.2 in vegetable and flowering crops [50]. Interestingly, the N200_PKdec treatment, which saw decreased chlorophyll contents, resulted in increased stomatal conductance. This enhanced gas exchange allows for greater CO_2 uptake, potentially acting as a strategy to offset the reduced photosynthetic rate [51,52]. Given usual growing conditions, purslane acts like a C4 plant, but during drought, it converts to the CAM pathway. Purslane's transition to the CAM pathway, a very water-efficient photosynthetic system, undoubtedly aids in its survival during drought [2]. The decreased stomatal conductance observed in the present study, mainly at the lower N levels (100 mg L^{-1}) and the relevant increased MDA levels might be related to the ability of purslane to recognize stress conditions (as it does under drought) and to function as CAM or C4 depending on the environmental conditions. It has been reported that purslane's drought resistance and water usage efficiency were improved by altering its CAM pathways [2,53]. Moreover, purslane plants grown using increased (1.66-fold) levels with 100 mg N L^{-1} in the NS had the highest TSS percentage. The lowest TSS was recorded with N200_PKinc. Similarly, Chrysargyris and Tzortzakis [25] observed that purslane grown in >100 mg N L^{-1} had decreased TSS. Increases in osmolytes, including proline, ascorbic acid, and TSS, are produced to protect plant tissue against hyperosmotic stress [54,55]. Therefore, the highest TSS found in increased (1.66-fold) levels with 100 mg N L^{-1} in the NS is mirrored to the increased MDA levels, indicating stress conditions for the plants. Notably, the study of Nofal et al. [56] on lettuce demonstrated a positive correlation between increased K fertilization and increased TSS and ascorbic acid. This was attributed to the role of K in photosynthesis, the activation of enzymes and adenosine triphosphate (ATP) production. In fact, decreased (0.66-fold) P and K levels in the current study led to a decrease in ascorbic acid. However, the highest ascorbic acid content was observed with the application of normal (1-fold) levels of P and K, using 200 mg N L^{-1} in the nutrient solution. This increase may be linked to the increased production of ascorbic acid under hyperosmotic stress [25,54].

The different NPK rates applied in the current study impacted the macronutrient content in leaves, stems and roots, as well as NUE and WUE. The content of nitrogen in leaves and roots was positively influenced by the increased (1.66-fold) levels of P and K, at 100 mg N L^{-1}. This, however, did not occur with the application of 200 mg N L^{-1}, as the N contents in leaves and roots were decreased. Chrysargyris et al. [4] observed that the modification of N in the NS, ranging from 50 to 300 mg L^{-1}, did not influence the uptake and accumulation of N in purslane plant tissues. Similar findings were reported by Montoya-García et al. [57], when both N and P fertilization rates were increased in the field cultivation of purslane. Moreover, El-Sherbeny et al. [46] reported an increase in N accumulation in leaves with the increase in K fertilization rates in soil-grown plants. However, the researchers also noted that the modification of the NPK ratio, and the increase in N, led to an increase in N in leaves and stems. Increased rates of K can negatively affect the absorption of Ca and Mg [58]. In the current study, this effect was observed with the application of N200_PKinc, where Ca and Mg in leaves and stems were decreased. This is accompanied by an increase in the K in leaves and is directly related to the increased K concentrations in the NS and the lower N:K ratio, as previously observed in lisianthus

(*Eustoma grandiflorum* [Raf.] Shinn) [59]. However, the application of N100_PKinc in the NS did not reveal the same results. The Ca and Mg obtained in the current study ranged from 6.77 to 17.64 g Ca kg^{-1} and 9.06 to 22.33 g Mg kg^{-1} for leaves, and from 1.55 to 3.82 g Ca kg^{-1} and 3.10 to 10.84 g Mg kg^{-1} for stems. These values matched those by D'Imperio et al. [60], ranging from 11.8 to 19.1 g Ca kg^{-1} and 17.3 to 18.8 g Mg kg^{-1} in edible purslane parts. Both WUE and NUE were increased with the application of the increased (1.66-fold) levels of P and K, at 100 and 200 mg N L^{-1}, although N100_PKdec had similar values. This suggests that, although higher rates of P and K positively influenced WUE and NUE, the lowest application of P and K using 100 mg N L^{-1} was more sustainable due to the lower use of fertilizers. In all instances, the application of 100 or 200 mg N L^{-1} did not have a significant influence on NUE, as suggested by Chrysargyris et al. [4].

When it comes to producing high-quality purslane, hydroponics has demonstrated encouraging outcomes, with higher levels of flavonoids, total phenolics, and antioxidant activity [40]. Plant polyphenols and flavonoids are antioxidants that have an important role in preventing chronic illnesses, due to their radical scavenging capabilities. These compounds are produced throughout the plants' development for various reasons, including defense against insects and microorganisms, ultraviolet radiation and allelopathic interactions. The formation of secondary metabolites is influenced by fertilization practices, particularly the availability of essential macronutrients like N, P, and K [61]. For instance, decreased N supply had positive effects on the biosynthesis of flavonoids [62], as demonstrated by Chrysargyris et al. [4], who observed an increase in the accumulation of phenols and flavonoids in purslane with the application of decreased levels of N (50 mg L^{-1}), as well as an increase in the antioxidant activity (assayed by DPPH and FRAP) with the application of 100 mg N L^{-1}, compared to 200 mg N L^{-1}. In the current study, however, the lower N level (100 mg L^{-1}) applied, significantly decreased flavonoids and antioxidants (assayed by DPPH, FRAP and ABTS), with the recommended (1-fold) levels of P and K in the nutrient solution. In contrast, the same N application led to an increase in phenols, flavonoids and antioxidants with elevated (1.66-fold) levels of P and K. Indeed, in previous studies, the N fertilizer increased biomass weight, fatty acid content, flavonoid content, overall antioxidant capacity, and P and N absorption [63], indicating the importance of a balanced fertilization scheme for plant growth. Generally, the lack of N deficiency is associated with decreased antioxidant activity and related compounds. However, the variation observed in the current study may be attributed to the changes in the N:K ratio, which significantly affects the production of secondary metabolites [64]. Potassium is known for its impact on various processes, including biotic and abiotic stress response [65,66]. Therefore, optimal N and K applications and a sufficient supply of K guarantee higher quality and yield [67]. In addition, P deficiency has shown to have a positive effect on the antioxidant activity, and it increases the oxidative stress of medicinal plants [68,69]. In the current study, H_2O_2 remained unaffected by the examined NPK ratios, suggesting that SOD activity effectively managed the accumulation of H_2O_2 under these conditions. However, MDA remained decreased with the application of recommended (1-fold) levels of P and K, compared to decreased (0.66-fold) and increased (1.66-fold) levels. This could indicate that under recommended P and K levels, plants are managing their stress response, preventing oxidative damage. This may also explain the increase in CAT, as the plants are undergoing adaptive responses to combat reactive oxygen species (ROS) [4,70].

5. Conclusions

The current study affirmed the viability of intensive cultivation methods, such as hydroponic NFT systems, in the production of purslane plants on a commercial scale. This study demonstrated the significant influence of NPK ratios in the hydroponic NS, on the

growth, yield, and quality of purslane. The decreased levels of P and K (47 and 250 mg L^{-1}, respectively) negatively affected chlorophylls content at 200 mg N L^{-1}, possibly due to the low N:K ratio. The recommended levels of P and K (70 and 350 mg L^{-1}, respectively) resulted in relatively decreased lipid peroxidation (MDA content), as plants are managing their stress response, as observed by an increase in CAT activity. The use of both N100_PKinc and N200_PKinc was characterized by an increased nutrient use efficiency, resulting in higher yield and enhanced plant growth. In addition, the use of N100_PKinc produced plants with increased quality as indicated by the increased antioxidant capacity of purslane. These findings suggest that both NSs (N200_PKinc and N100_PKinc) have potential benefits for the hydroponic cultivation of purslane, with the latter NS offering an additional advantage in terms of produce quality. Further research could explore other aspects of the nutrient solution (e.g., K:Ca:Mg ratio, micronutrients), to further standardize the production of purslane in hydroponic systems. Furthermore, parameters including the hydroponic system, consecutive harvests and biofortification should be examined to enhance the nutritional value of the final product.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy15010111/s1, Figure S1: Effect of nitrogen (N) concentration (100–200 mg L^{-1}; as N100, N200) in combination with different levels (decreased 0.66-fold: dec, recommended 1-fold: rec, or increased 1.5-fold: inc) of phosphorus (P; 47–70–105 mg L^{-1}) and potassium (K; 250–350–525 mg L^{-1}) in the electrical conductivity and pH of the drainage nutrient solution from purslane plants grown hydroponically in NFT system.

Author Contributions: Conceptualization, A.C. and N.T.; methodology, A.C. and N.T.; software, A.C.; validation, A.C. and N.T.; formal analysis, A.C.; investigation, A.C. and N.T.; resources, N.T.; data curation, A.C.; writing—original draft preparation, A.C. and N.T.; writing—review and editing, A.C. and N.T.; visualization, A.C.; supervision, N.T.; project administration, N.T.; funding acquisition, N.T. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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