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Yield and fruit quality of sweet pepper in response to fertilisation with Ca^{2+} and K^+

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Abstract

The influence of Ca^{2+} and K^+ levels on fruit yield and quality of sweet pepper (*Capsicum annuum* L. cv. Orlando) plants under hydroponic culture has been investigated. The treatments consisted of three concentrations of Ca^{2+} (1.5, 4 and 8 mmol L^{-1}) and K^+ (2.5, 7 and 12 mmol L^{-1}) that were imposed separately. Fruit yield parameters and different fruit quality parameters, as well as dry matter production and mineral composition in individual parts of the plant, were determined. The increase of Ca^{2+} in the root medium increased the marketable yield from 1.67 to 2.38 kg $plant^{-1}$, mainly due to an increase in the number of fruits per plant, while higher K^+ levels decreased marketable yield from 2.2 to 1.66 kg $plant^{-1}$, due to decreases in the number of fruits per plant and the mean fruit weight. With respect to fruit quality, fruit shape index and, therefore, pepper fruit appearance improved with Ca^{2+} addition to the root medium. Fertilisation with K^+ increased fruit acidity and decreased maturity index, which could improve fruit storability. Low Ca^{2+} or high K^+ levels reduced both root and shoot dry matter. Therefore, an adequate management of fertilisation with Ca^{2+} and K^+ could improve the yield and fruit quality of pepper grown in soilless culture.

Additional key words: *Capsicum annuum* L. cv. Orlando, greenhouse, Hoagland nutrient solution, hydroponics, plant nutrition.

Resumen

Rendimiento y calidad de los frutos de pimiento en respuesta a la fertilización con Ca^{2+} y K^+

Se investigó el efecto del Ca^{2+} y del K^+ sobre el rendimiento y la calidad de los frutos en plantas de pimiento (*Capsicum annuum* L. cv. Orlando) crecidas en cultivo hidropónico. Los tratamientos consistieron en tres concentraciones de Ca^{2+} (1,5, 4 y 8 mmol L^{-1}) y tres de K^+ (2,5, 7 and 12 mmol L^{-1}), que fueron comparadas de forma separada. Se determinaron los parámetros de rendimiento y la calidad de los frutos, así como la producción de materia seca y composición mineral en la parte aérea, raíces y frutos. El aumento de la concentración de Ca^{2+} en la solución nutritiva incrementó el rendimiento comercial de 1,67 a 2,38 kg $planta^{-1}$, al aumentar el número de frutos por planta. La mayor concentración de K^+ ensayada (12 mmol L^{-1}) disminuyó el rendimiento de frutos comerciales de 2,2 a 1,66 kg $planta^{-1}$, debido al descenso del número de frutos por planta y del peso medio de los frutos. El índice de forma de los frutos, y por tanto, su apariencia, mejoró con la adición de Ca^{2+}. Por su parte, el aumento de K^+ incrementó la acidez de los frutos y disminuyó el índice de madurez, lo que podría facilitar el almacenaje de los frutos. El crecimiento de la parte aérea y de la raíz disminuyó con 1,5 mmol L^{-1} de Ca^{2+} o con 12 mmol L^{-1} de K^+. De esta forma se concluye que un manejo adecuado de la fertilización con Ca^{2+} y K^+ podría mejorar el rendimiento y la calidad de los frutos en pimiento crecido en cultivo sin suelo.

Palabras clave adicionales: *Capsicum annuum* L. cv. Orlando, cultivo hidropónico, invernadero, nutrición vegetal, solución nutritiva Hoagland.

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Abbreviations used: BER (blossom end rot), DM (dry matter), EC (electrical conductivity), FSI (fruit shape index), MI (maturity index), TSS (total soluble solids).

Introducción

Pepper is an important horticultural crop in many regions of the world. In Spain, the half of the horticultural crops (5,000 ha) is being grown in greenhouse under soilless system (Urrestarazu, 2004), around half corresponds to rockwool and the other half to perlite, sand, coir and other minor soilless systems. The study of the effect of the major macronutrients on fruit yield and quality under controlled nutrient solution could be used for improving pepper culture in soilless systems with maximum efficiency in the use of fertilizers.

Calcium plays a key role in plant growth and fruit development and it is involved in many biochemical and physiological processes (Saure, 2005). Even under non-saline conditions, significant economic losses of horticultural crops have been linked to inadequate calcium nutrition (Grattan and Grieve, 1999). Thus, calcium-related disorders may occur in plants where the calcium concentration appears to be adequate as well as where the calcium content is low (Bernstein, 1975). Potassium is one of the major macronutrients, contributing up to 6% of plant dry weight (Shabala, 2003) and it is considered to be a key factor for fruit quality (Hartz *et al.*, 1999). The findings about the influence of K^+ on pepper fruit quality are related to nutritional quality (Flores *et al.*, 2004), while the findings about the influence of K^+ on pepper yield are related basically to the amelioration of the negative effects of salinity stress (Kaya and Higgs, 2003) or to ammonium-potassium interactions (Xu *et al.,* 2002).

The influence of mineral nutrition on quality characteristics, such as soluble solids, acidity and pH, and on physical characteristics, such as fruit shape index, firmness and pulp thickness, has been not very much studied in pepper plants and it is important for both fresh and processed horticultural crops, as has been observed in tomato (*Solanum lycopersicum* L.) by Cuartero and Fernández-Muñoz (1999).

The importance of the main nutrient elements regarding the yield and quality components of pepper plants requires further study; this will be necessary in order to develop a rational fertilisation in soilless systems. In this respect, there is a scarcity of studies on pepper plants using concentrations of the nutrients similar to those used by growers. We hypothesise that current nutritional equilibriums based on the Hoagland nutrient solution could be adapted for sweet pepper in order to improve the yield and fruit quality. Thus, the aim of this research was to study the effects of different levels of Ca^{2+} and K^+ on the fruit yield and quality parameters of pepper plants grown in hydroponic culture. The mineral composition of the organs and plant dry matter production were also measured.

Material and methods

Growth conditions and treatments

The experiments were conducted under controlled-greenhouse conditions in Murcia (38°6' N, 1°1' W; altitude 155 m), Southeast Spain, during the winter-spring season. The greenhouse of 500 m^2 is equipped with cooling system, heating system and fog system. The climate conditions were computerized, ranging the relative humidity from 60 to 70% (day) and from 75 to 85% (night), and the air temperature from 25 to 30°C (day) and from 17 to 23°C (night). Seeds of pepper plants (*Capsicum annuum* L. cv. Orlando) were sown in cell pots ($2\times3\times10$ cm) filled with vermiculite. After the second true leaf appeared, one homogeneous seedling was transferred into each of 40 continuously-aerated, 120-L capacity containers, covered with black, hard PVC to exclude light from the roots and to prevent evaporation. The plant density was 1.66 plant m^{-2} with 0.5 m between plants in the same row and 1.2 m between rows. Treatments were initiated immediately after transplanting seedlings into the containers. The basic nutrient solution (control) consisted of a modified Hoagland solution (Table 1), which was modified by elimination of some of the salts or by addition of $CaCl_2$, $NaNO_3$, K_2SO_4 and NaH_2PO_4 when necessary (Table 1), in order to obtain five different treatments: control, low calcium (1.5 mmol L^{-1} Ca^{2+}), low potassium (2.5 mmol L^{-1} K^+), high calcium (8 mmol L^{-1} Ca^{2+}) and high potassium (12 mmol L^{-1} K^+). The micronutrients were applied similarly in all the treatments, in the following form: 25 µmol L^{-1} H_3BO_3, 2 µmol L^{-1} $MnSO_4.H_2O$, 2 µmol L^{-1} $ZnSO_4.7H_2O$, 0.5 µmol L^{-1} $CuSO_4.5H_2O$, 0.5 µmol L^{-1} $(NH_4)_6\ Mo_7O_{24}.4H_2O$ and 20 µmol L^{-1} Fe^{3+}-EDDHA. The experimental design consisted of four randomised blocks with five treatments. Each treatment consisted of eight replicates (two per block).

During the growth period, the volume of the nutrient solutions was maintained by adding deionised water daily. All solutions were analysed weekly and readjusted to initial concentrations when necessary. The pH was kept within the range of 5.5-6.0 by adding 1 mol L^{-1} H_2SO_4 or 0.5 mol L^{-1} KOH. Each plant was trained into

Table 1. Concentration of macronutrients (mmol L^{-1}) and electrical conductivity (EC, dS m^{-1}) in the nutrient solution of the treatments

Nutrient source	Control	Low Ca^{2+}	High Ca^{2+}	Low K^+	High K^+
KNO_3	6	5	0	2.5	5
$Ca(NO_3)_2.4(H_2O)$	4	1.5	7	4	4
$NaNO_3$	0	6	0	3.5	1
K_2SO_4	0	0	3	0	3
$MgSO_4.7(H_2O)$	1	1	1	1	1
$NaH_2PO_4.2(H_2O)$	0	0	1	1	0
KH_2PO_4	1	1	0	0	1
KCl	0.05	0.05	0.05	0.05	0.05
$CaCl_2.6(H_2O)$	0	0	1	0	0
EC	2.0	1.9	2.3	1.8	2.3

two main stems and at each internode only three leaves were left attached. The experiment was terminated 196 days after transplanting.

Fruit sampling

Fruits were usually harvested weekly according to the time of ripening, starting on day 114 after transplanting, until the end of the experiment. Yield was determined by counting and weighing all fruits on each plant. In addition, length and diameter were also recorded for all fruits. Only marketable yield, based on marketable characteristics for red California pepper (Navarro *et al.*, 2002), was taken into account for the experiment. Fruits with more than 20% of blossom-end rot (BER), rotten fruits and fruits of fresh weight lower than 100 g were not taken into account for marketable yield.

Fruit analysis

Fruit firmness, fruit shape index (FSI) and pulp thickness were determined in two selected fruits per plant (16 per treatment) with intact skin and uniform colour, from the 2nd and 3rd trusses. Fruit pulp firmness was determined on three sides of each fruit, in the equatorial area, using a penetrometer (Bertuzzi FT 011) fitted with an 8-mm diameter probe. Fruit shape index (FSI) was defined by the equatorial to longitudinal length ratio. The selected fruits were then cut and pulp thickness measured.

Chemical fruit quality was determined in the same 16 fruits used for the physical analyses. The fruits were liquefied and filtered for pH, total soluble solids content (TSS), acidity and maturity index (MI) determinations. In the extract obtained by liquefying the mesocarp of each fruit, TSS in juice was determined by an Atago N1 refractometer and expressed as °Brix at 20°C. Ten millilitres of juice were assayed by potentiometric titration with 0.1 mol L^{-1} NaOH to pH 8.1. Results were expressed as a percentage of citric acid in the juice. Maturity index was expressed as the soluble solids/acidity ratio.

Mineral composition and dry matter determinations

At the end of the experiment, plants were separated into roots, stems and leaves. Each plant organ was washed with deionised water, dried in a forced oven at 70°C for 48 h and weighed, to determine shoot (leaf + stem) and root dry matter (DM). The mineral composition was determined in all plant organs and fruits. Mineral composition of leaf and stem was expressed as shoot mineral composition. The extraction of K^+, Ca^{2+} and Mg^{2+} from the plant tissues was performed by a HNO_3-$HClO_4$ (2:1) digestion: K^+ was determined by atomic emission and Ca^{2+} and Mg^{2+} by atomic absorption with a Perkin-Elmer 5500 spectrometer. Nitrate was extracted with water and determined by ion chromatography, using conductivity detection (Dionex DX-100), an Ionpac AG12A guard column and an Ionpac AS12A analytical column. The mobile phase was 2.7 mmol L^{-1} Na_2CO_3/0.3 mmol L^{-1} $NaHCO_3$.

Statistical analysis

Analysis of variance was performed to assess the significance of treatment effects. Differences between treatment means were compared by using Tukey's multiple range test at the 0.05 probability level. Levels of significance are represented as follows: $*P<0.05$; $**P<0.01$; $***P<0.001$; NS, not significant.

Results

Fruit yield and quality

The increase of Ca^{2+} in the root medium from 1.5 to 8 mmol L^{-1} resulted in a significant increase of marketable fruits (39.5%) (Fig. 1a). From 1.5 to 4 mmol L^{-1} Ca^{2+}, this increase was due to a rise in both the weight and number of fruits per plant (Figs. 1b and 1c), whereas the increase in marketable fruit from 4 to 8 mmol L^{-1} Ca^{2+} was a result of the increase in the number of fruits per plant (11% above the control).

At the high K^+ level (14 mmol L^{-1}), marketable fruit yield was reduced (by 25%) compared to the low and medium K^+ levels, as a result of a decrease in both the number of fruits per plant and the mean fruit weight (Figs. 1d, 1e and 1f). There were no significant differences in yield components between the low and control K^+ levels (2.5 and 7 mmol L^{-1}) (Figs. 1e and 1f).

The percentages of non-marketable fruits in all treatments were very low (data not shown) and there were no significant differences among treatments. Fruit quality parameters were affected by the different treatments (Table 2). Fruit shape index increased with the highest Ca^{2+} concentration in the root medium. In addition, the lowest Ca^{2+} level decreased the TSS and increased the pH. Acidity increased gradually with increasing K^+ level through the studied range of 2.5 to 14 mmol L^{-1}, and a significant decrease in the maturity index with increased K^+ level in the root medium was observed.

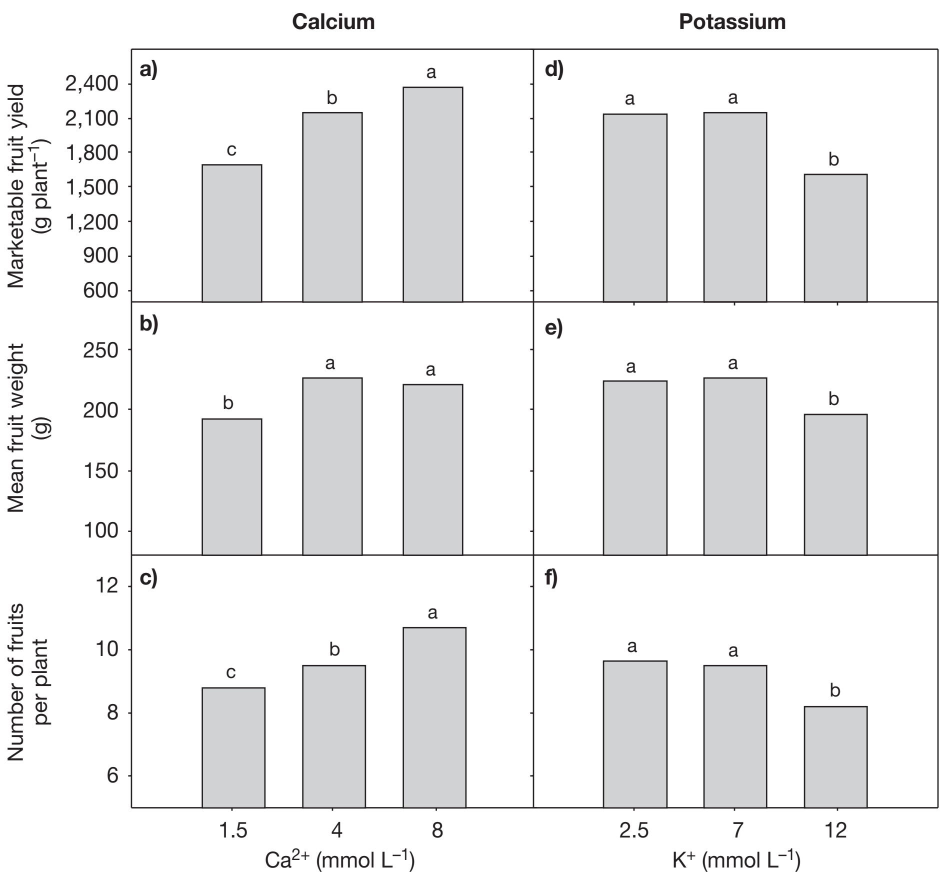

Figure 1. Effects of calcium and potassium treatments on marketable fruit yield (g $plant^{-1}$), mean fruit weight (g) and number of fruits per plant. Each column represents the mean of eight replicates. Columns with different letters indicate significant differences at $P<0.05$ between treatments, according to Tukey's test.

Table 2. Effects of Ca^{2+} and K^+ treatments on constituents and quality parameters of pepper fruits grown in hydroponic culture

Treatment	Concentration (mmol L^{-1})	Fruit shape index	Firmness (N cm^{-2})	Pulp thickness (mm)	pH	TSS (°Brix)	Acidity (g citric acid 100 mL^{-1} juice)	Maturity index
Calcium	1.5	0.73^a	4.49	7.00	5.45^a	8.62^a	0.22	40.09
	4	0.80^a	4.47	6.95	5.26^b	9.00^b	0.21	42.36
	8	0.96^b	4.43	7.28	5.25^b	9.18^b	0.23	40.75
		***	NS	NS	*	***	NS	NS
Potassium	2.5	0.78	4.63	7.42	5.28	8.90	0.20^a	44.43^a
	7	0.80	4.47	6.95	5.26	9.00	0.21^a	42.36^{ab}
	14	0.77	4.73	6.91	2.27	9.10	0.24^b	38.22^b
		NS	NS	NS	NS	NS	***	**

*, ** and ***: significant differences between means at 0.05, 0.01 and 0.001 level of probability, respectively. NS: non-significant. Different letters indicate significant differences between treatments according to Tukey's test. Values are means of 16 fruits.

Shoot-root dry matter and mineral composition

Shoot and root dry matter were significantly lower at low Ca^{2+} and at high K^+ levels in comparison with the other treatments (Figs. 2a, 2b, 2c and 2d). The decreases in shoot and root dry matter (about 26%) were similar for the low Ca^{2+} and high K^+ treatments with respect to the control.

Shoot, root and fruit Ca^{2+} concentrations were increased by addition of Ca^{2+} to the root medium (Table 3). The increase of Ca^{2+} in the root medium from 1.5 to 8 mmol L^{-1} increased root Ca^{2+} concentration 6 times more than shoot Ca^{2+} concentration. The concentrations of K^+ in shoots and fruits were not affected by the Ca^{2+} treatments, whereas root K^+ concentration decreased when the Ca^{2+} level increased from 4 to 8 mmol L^{-1}. The Mg^{2+} concentration in shoot and root decreased as the Ca^{2+} levels in the root medium increased. Root NO_3^- concentration was decreased significantly by increasing Ca^{2+} concentration in the root medium.

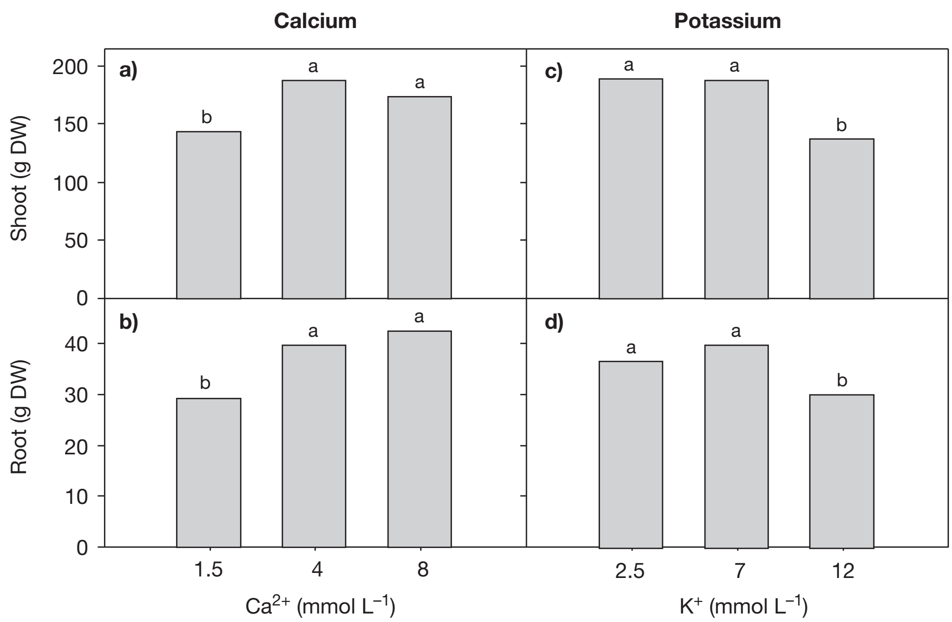

Figure 2. Effect of calcium and potassium treatments on dry weight (DW) of shoot and root at the end of the experiment. Columns with different letters indicate significant differences at $P < 0.05$ between treatments, according to Tukey's test.

Table 3. Macronutrient concentrations (mmol kg^{-1} DM) in shoot, root and fruit at the end of the experiment, as affected by Ca^{2+} treatments

Part of plant	Ca^{2+} (mmol L^{-1})	Potassium	Calcium	Magnesium	Nitrate
Shoot	1.5	1,302	558^{c}	250^{a}	477
	4	1,401	678^{b}	215^{b}	493
	8	1,320	885^{a}	201^{b}	506
		NS	***	**	NS
Roots	1.5	1,397^{a}	132^{c}	219^{a}	1,207^{a}
	4	1,288^{a}	254^{b}	201^{ab}	1,069^{b}
	8	1,048^{b}	845^{a}	174^{b}	771^{c}
		**	***	*	***
Fruits	1.5	572	15.4^{b}	46.3	ND
	4	593	16.0^{b}	48.1	ND
	8	586	23.7^{a}	47.3	ND
		NS	***	NS	

Values are the means of eight replicates. ND: non-detectable. *, ** and ***: significant differences between means at 0.05, 0.01 and 0.001 level of probability, respectively, according to analysis of variance. NS: non-significant. Different letters indicate significant differences between treatments according to Tukey's test.

The K^+ concentrations in the different plant organs showed similar values; except for the fruits, where the K^+ concentration was approximately half of that in the other parts of the plant (Table 4). Decreasing K^+ in the root medium from 7 to 2.5 mmol L^{-1} decreased significantly shoot and root but not fruit K^+ concentrations. In shoots, Ca^{2+} concentrations were increased significantly at the low K^+ level in the root medium, compared to the high K^+ level, whereas root Ca^{2+} concentrations were reduced significantly by high K^+ in the medium. Fruit mineral composition was not affected by the K^+ treatments.

Discussion

Effect of calcium

Fruit marketable yield responded positively to the increase of Ca^{2+} supply, which increased the number

Table 4. Macronutrient concentrations (mmol kg^{-1} DM) in shoot, root and fruit at the end of the experiment, as affected by K^+ treatments

Part of plant	K^+ (mmol L^{-1})	Potassium	Calcium	Magnesium	Nitrate
Shoot	2.5	1,203^{b}	757^{a}	225	454
	7	1,401^{a}	678^{ab}	215	493
	14	1,409^{a}	658^{b}	199	470
		**	**	NS	NS
Roots	2.5	1,145^{b}	279^{a}	219	1,034
	7	1,288^{a}	254^{a}	201	1,069
	14	1,298^{a}	160^{b}	190	961
		*	**	NS	NS
Fruits	2.5	596	14.4	45.5	ND
	7	593	16.0	48.1	ND
	14	593	14.6	47.5	ND
		NS	NS	NS	

Values are the means of eight replicates. ND: non-detectable. *, ** and ***: significant differences between means at 0.05, 0.01 and 0.001 level of probability, respectively, according to analysis of variance; NS: non-significant. Different letters indicate significant differences between treatments according to Tukey's test.

and weight of the fruits (Fig. 1). Alexander and Clough (1998) observed an increase of pepper marketable yield due to increased Ca^{2+} supply, mainly because of an increase in extra large marketable fruits and a decrease in BER-affected fruits. Our results indicate that Ca^{2+} improved total yield (data not shown), since the percentage of non-marketable fruits was similar in all treatments and the incidence of BER was very low, possibly due to the high relative humidity maintained throughout the experiment. Several studies have shown a reduction in BER severity in tomatoes under conditions of low vapour pressure deficit (Bradfield and Guttridge, 1984; Adams and Holder, 1992). On the other hand, in our experiment, it is necessary point out that the lower fruit yield obtained in comparison with yields (by 4 kg plant^{-1}) of industry pepper was due to our experimental period was from December-May while in the commercial greenhouses the plant are kept until August or September.

The fruit shape index (FSI) is an important characteristic of California peppers, since this, together with the weight, determines the fruit category (Navarro *et al.*, 2002). In our experiment, the increase in Ca^{2+} level in the root medium tended to increase FSI, fruits with high shape quality being obtained in the 8 mmol L^{-1} Ca^{2+} treatments. In addition, greater Ca^{2+} in the root medium decreased pH and increased TSS in the fruit.

The increase of Ca^{2+} concentration from 1.5 to 4 mmol L^{-1} increased root and shoot dry weight, however, a further increase from 4 to 8 mmol L^{-1} slightly, but non-significantly, affected root growth (Fig. 2). Although leaf Ca^{2+} concentration (data not shown) was within the normal range of concentrations described in the literature (Bergman, 1992), it is clear that the 1.5 mM Ca^{2+} treatment gave rise to a Ca deficiency since it limited root growth. At 1.5 mmol L^{-1} Ca^{2+}, only 5% of the total Ca^{2+} content of the whole plant was in the root, while with 8 mmol L^{-1} Ca^{2+}, 20% was in the root. This different pattern of Ca^{2+} distribution within the plant as a function of the concentration in the root medium could be the cause of the differences observed in vegetative growth, which affected the fruit weight and number. The beneficial effects of Ca^{2+} supply on root dry matter and yield could be a consequence of the close positive correlation between membrane stability and maintenance of cell integrity and calcium content in plant tissues (Epstein and Bloom, 2005). On the other hand, although increasing Ca^{2+} decreased significantly the shoot and root Mg^{2+} concentrations and the root K^+ and NO_3^- concentrations, the concentrations of these nutrients were within their normal ranges, indicating that the small variations of these nutrients were not responsible for the effects of Ca^{2+} on yield and growth.

Effect of potassium

The highest biomass production and marketable yield were obtained with 2.5 and 7 mmol L^{-1} K^+. The higher K^+ concentration (14 mmol L^{-1}) reduced biomass and marketable yield by about 26%. In pepper plants grown on recycled solution, Xu *et al.* (2002) found that low K^+ concentration (0.5 mmol L^{-1}) produced high early fruit yield, while Johnson and Decoteau (1996) found that at least 6 mmol L^{-1} K^+ is required for optimum fruit production. In perlite, pepper production is not affected in the range between 2.75 and 6 mM of K^+ in the nutrient solution (García-Lozano *et al.*, 2005). In our experiment, the negative response of plant growth and marketable yield to increasing K^+ could be due, at least in part, to the interaction between K^+ and Ca^{2+} at the uptake level (Marschner, 1995). The Ca^{2+} concentrations in shoots and roots at 14 mmol L^{-1} K^+ were similar to those found at the lowest Ca^{2+} level (1.5 mmol L^{-1}), which was related with the lower plant growth and fruit yield.

High K^+ levels increased fruit acidity and decreased maturity index. Titratable acidity reached 0.24% of citric acid at 14 mmol L^{-1} K^+. A specific role of K^+ in controlling fruit acidity has been found in tomato (Adams, 1991). These effects of K^+ on fruit could enhance storage and also extend their shelf-life (Usherwood, 1985).

It can be concluded that yield could be increased and fruit quality optimised by modifying the concentrations of Ca^{2+} and K^+ present in the modified Hoagland solution used as the control nutrient solution. In the studied ranges of Ca^{2+} and K^+ concentrations, the highest pepper yields were obtained with 8 mmol L^{-1} Ca^{2+} and 2.5 mmol L^{-1} K^+. Therefore, higher Ca^{2+} and lower K^+ concentrations than those commonly used (Johnson and Decoteau, 1996; Bar-Tal *et al.*, 2001; Navarro *et al.*, 2002) can be recommended for pepper culture. It would be interesting to investigate the effect of a modified nutrient solution that combines high Ca^{2+} with low K^+. In addition, further studies are required to test our results in other season and with different substrates.

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