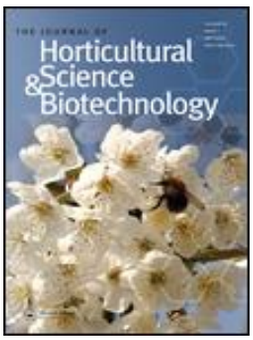

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Potassium nutrition and postharvest moisture loss in carrots (*Daucus carota* L.)

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SUMMARY

The effect of potassium (K) nutrition on the shelf life of carrots (*Daucus carota* L., cv. Paramount) was studied using a hydroponic system involving rockwool slabs as an inert support. Carrots were grown for 192 d under greenhouse conditions and with 0, 0.1, 1.0, 10 and 15 mM K supplied in the nutrient medium. Increase in K concentration in the nutrient medium up to 1 mM decreased postharvest moisture loss. Carrot root weight and tissue K concentration increased, and water potential, osmotic potential and relative solute leakage decreased with increasing K concentration up to 1 mM. Concentrations greater than 1 mM had little or no additional effect on postharvest moisture loss, root water and osmotic potentials and relative solute leakage. Root weight did not increase above 10 mM K. The best subset model obtained by backward stepping and the optimum Mallow's coefficient showed that carrot root weight and relative solute leakage accounted for most of the variation in moisture loss. Root weight correlated negatively and relative solute leakage positively to moisture loss.

Wilting and shrivelling due to postharvest transpirational moisture loss lowers the quality of vegetables (Hardenburg *et al.*, 1986). Postharvest moisture loss increases susceptibility to disease (van den Berg and Lentz, 1973), reduces vitamin C and carotene contents, marketable weight, and the economic value of vegetables (Hardenburg *et al.*, 1986). Air velocity, temperature, relative humidity, plant nutrition, and physical and physiological conditions of the produce influence moisture loss in fruits and vegetables during storage (Fockens and Meffert, 1972; Ben-Yehoshua, 1987).

K plays an important role in activation and stabilization of enzymes and membranes (Wyn Jones and Pollard, 1983; Suelter, 1985), protein and starch synthesis (Hsiao, 1976), and membrane transport (Cheeseman and Hanson, 1980). It is needed for the operation of the K^+-shuttle system, which mediates the transport of nutrients and photosynthates between roots and shoots (Ben-Zioni *et al.*, 1971), regulation of osmotic and turgor pressures, and cell volume maintenance (Raschke, 1979). In growing plants, it is a major contributor to osmotic potential (ψ_π), a component of water potential (ψ) which determines water uptake by roots. It also plays an important role in the regulation of stomatal opening in leaves (Raschke, 1979; Salisbury and Ross, 1991) which in turn affects foliar transpiration.

Plant nutrition can influence the rate of postharvest moisture loss through its effect on produce size and physiology. Habben (1972) reported an increase in root size with increasing level of K fertilization when carrots were grown in low-K peat and loam soils. Biegon (1995), however, found no effect in high-K muck soil. Whether the size differences due to soil K level lead to differences in postharvest moisture loss is not known.

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In potatoes and onion bulbs, K has been shown to improve storability (Kunkel, 1947; Lune and Goor, 1977) but the mechanism of this effect is not understood. Biegon (1995) found no effect of K level and source (KCl vs K_2SO_4) on postharvest moisture loss from carrots grown on high-K muck soil. The influence of lower levels of K on postharvest moisture loss in carrots has not been investigated. The objectives of this study were, therefore, to determine the effects of low to moderate levels of K nutrition on postharvest moisture loss in carrots and the physiological basis of this effect.

MATERIALS AND METHODS

Seeds of carrot (*Daucus carota* L., cv. Paramount; Asgrow Seed Co., Newmarket, Ontario) were sown between May and November (in 1993) and February and August (in 1995) in rockwool slabs (Pargro Ltd., Caledonia, Ontario) placed in 6 l plastic pots (10 seeds per pot) in a greenhouse at the University of British Columbia. Each pot contained two 70 mm wide × 150 mm long × 220 mm high rockwool slabs. Seedlings were thinned to three per slab (i.e. six per pot) one month after sowing. A modified Hoagland and Arnon (1950) No. 2 solution was used as nutrient medium. The treatments were 0.0, 0.1, 1.0, 10 and 15 mM of K. K_2SO_4 in place of KNO_3 was used as a source of K (since the use of the latter would lead to a variation in plant N, a major plant nutrient). Other salts added to the medium were: 4 mM Ca $(NO_3)_2$ $4H_2O$, 1 mM $NH_4H_2PO_4$, 2 mM $MgSO_4$ $7H_2O$, 9 μM MnCl $4H_2O$, 46 μM H_3BO_3, 0.8 μM $ZnSO_4$ $7H_2O$, 0.2 μM $CuSO_4$ $5H_2O$ and 0.1 μM MoO_3. Iron was supplied as sequestrene at 5.0 ppm. The pots were arranged in a completely randomized design replicated six times.

The nutrient solution was applied at the rate of 200 ml per pot twice a week except on the weekends when the rockwool was flushed with tap water to prevent salt build up. The flushing water contained 5.2 μM K and was the only source of K responsible for growth of carrots at the lowest K treatment. A 1/4, 1/2 and full strength nutrient solution was applied in the first, second and third month of growth, respectively.

The plants were sprayed with Vendex (fenbutatin-oxide) (Dupont Co., Wilmington, DE) (for mite control) and Safer's insecticidal soap (Safer Inc., Concord, MA) (for white fly control) every seventh day. The average greenhouse temperature varied from 18 to 30°C, the relative humidity from 35 to 65%, and solar irradiance from 150 to 465 μmol m^{-2} s^{-1}. Plants were harvested after 192 d. Harvesting was done by carefully separating rockwool material from the roots followed by removal of the leaf stalk. Three carrots from each pot (replicate) were used to determine postharvest moisture loss, one for ψ and ψ_π at harvest, and one for the relative solute leakage (RSL) characteristic of the carrot tissue at harvest.

Carrot size and postharvest moisture loss measurements

The carrot root weight (W), the widest diameter of the root (D) and root length (L) were measured on the three carrots sampled from each replicate for moisture loss studies as described above. The carrot shape (indicated by the C-value) and surface area (A) were calculated using the following formula of Bleadsdale and Thompson (1963) and Baugerød (H. Baugerød, Dept. of Vegetable Crops; Agric. College of Norway pers. comm.), respectively.

$$C = W/(\pi \times (D/2)^2 \times L)$$
$$A = (2\ \pi \times C \times D \times L)/(1 + C)$$

The carrots were then placed in 0.1 m × 0.22 m plastic bags with three, 6 mm diameter perforations and incubated at 13°C and 30 ± 5% r.h. Carrot weight loss was monitored every second day for 14 d. Carrots with a higher moisture loss were considered to have a shorter shelf life. Preliminary studies under similar conditions showed that weight loss was mainly due to moisture loss; respiration accounted for a negligible portion of weight loss during 21 d of storage. Moisture loss (W^p) at 14 d was expressed as a percentage of the original carrot root weight as well as on a per unit surface area basis [transpiration coefficient (TC)].

ψ and ψ_π measurements

Using a cork borer, 30 mm long cores were excised longitudinally from phloem parenchyma 2 h after harvesting. The cores were cut into 1 mm thick × 3 mm diameter discs which were placed in the sample well of a C-52 Thermocouple Psychrometer chamber (Wescor Inc., Logan, UT) connected to a Dewpoint Microvoltmeter (Model HR-33T, Wescor Inc., Logan, UT) in the psychrometer mode, calibrated with NaCl standards. During ψ measurement, the sample well was placed within a polystyrene container to minimize temperature fluctuations; the temperature was maintained at 22 ± 2°C. Samples were left for 30 min, a time found to be adequate to reach thermal and vapour equilibrium in preliminary studies.

ψ_π measurements were made on the same carrots as used for ψ measurements. Shredded pieces of phloem parenchyma were frozen at −85°C for two weeks, thawed at room temperature for at least 10 min, and crushed using a mortar and pestle. The sap was expressed from the crushed tissue and squeezed through two layers of Miracloth (Calbiochem-Novabiochem Corp., La Jolla, CA). ψ_π of the sap was measured by the molecular depression of freezing point method using a thermocouple connected to a micrologger (21-Micrologger, Campbell Scientific Inc., Logan, UT) calibrated with NaCl standards.

Tissue permeability measurement

RSL of the phloem parenchyma tissue from carrots grown under different concentrations of K in the growth medium ($[K^+]$) was measured. Cores (30 mm long), excised longitudinally from the phloem parenchyma of carrot roots using a 4 mm diameter cork borer, were cut into 1 mm thick discs and rinsed three times with deionized distilled water. The discs (25) were incubated in 25 ml deionized distilled water in 50 mm glass jars at 22 ± 2°C. After 24 h, absorbance of the incubation medium at 280 nm was measured using a spectrophotometer (Model UV 160, Shimadzu, Japan) to determine the total solute content. The tissue integrity was then destroyed by freezing at −85°C as described above. After thawing for 24 h, absorbance of the bathing medium was measured to determine the total solute content of the tissue. RSL, the ratio of the absorbance of the incubation medium before freezing and after tissue disintegration by freezing, was calculated (Toivonen, 1992).

K concentration in tissue (TK)

The tissue bathing medium after the destruction of tissue integrity, used for determination of the total solute content described above, was also used to determine TK. Aliquots (0.5 ml) of the medium were diluted with 6 ml of deionized distilled water. TK was measured using an atomic absorption flame photometer (Perkin-Elmer 806, Mountain Sites, Montreal, Quebec) at 766 nm, using calibration curves for KCl standards.

Statistical analysis

The significance of the effect of $[K^+]$ on the dependent variables (W, ψ, ψ_π, RSL and TK) was tested using orthogonal contrasts in the general linear models procedure of SAS statistical software (SAS, 1985). Coefficients for the non-equally spaced independent variable ($[K^+]$) were determined using an algorithm programmed into BASIC by Hall (1996). The linear and quadratic contrasts were found to be significant.

Stepwise multiple regression analysis using the means of W, ψ, ψ_π, RSL and TK (independent variables) and W^p (dependent variable) were carried out. The best fit model was determined from a set of models on the basis of a high R^2 value and the optimum Mallow's coefficient (Cp value) (Neter *et al.*, 1990). Combined exponential and power functions, and hyperbolic, linear and quadratic models were again fitted between each of the independent variables chosen in the best model and W^p.

TABLE I
The effect of K concentration in the growth medium on postharvest weight loss and physiological characteristics of carrots

Treatment [K^+] (mM)	Weight loss (%)	Transpiration coefficient (mg mm^{-2})	Root weight (g)	ψ (MPa)	ψ_π (MPa)	Relative solute leakage (%)	Tissue K (mM)
0.01	74.0	136.4	2.6	−0.52	−0.95	44.2	6.6
0.1	43.5	102.2	11.3	−0.56	−0.99	18.2	6.1
1.0	35.4	93.1	17.4	−0.68	−1.04	14.0	18.1
10.0	31.6	81.9	31.6	−0.74	−1.18	14.8	46.0
15.0	28.6	77.6	33.6	−0.72	−1.16	11.7	50.9
$LSD_{(P=0.05)}$	10.9	28.7	6.1	0.13	0.22	16.6	11.7
Significance[1]	L**, Q**	L**	L**	L**	L*	L**, Q*	L**

[1]L = linear trend, Q = quadratic trend, * = significant at $P = 0.05$, ** = significant at $P = 0.01$.

RESULTS

Percent moisture loss of carrots grown under different [K^+] differed following 14 d of storage (Table I). Increase in [K^+], up to 1.0 mM in the nutrient medium, resulted in a decrease in postharvest moisture loss. There were no significant differences in weight loss among carrots grown at 1.0, 10 and 15 mM K. An increase in [K^+] up to 0.1 mM resulted in a significant decrease in the transpiration coefficient (TC, water loss per unit surface area). There was no difference in TC among carrots grown at 1.0, 10 and 15 mM K.

Increase in [K^+] up to 10.0 mM increased carrot root weight (Table I). Higher concentrations had no further effect. Similarly, D and L increased up to 10.0 mM K and then levelled off (data not shown). Carrot root weight was more sensitive to [K^+] in nutrient medium than was weight loss, since weight loss showed a significant quadratic response with no significant change occurring beyond 1 mM K whereas root weight showed a significant linear response over the full range of [K^+].

ψ and ψ_π of the carrot roots decreased with increasing [K^+] (Table I). Changes in ψ and ψ_π were similar and it is therefore likely that ψ was predominantly determined by the ψ_π.

RSL of carrot tissue decreased with increase in [K^+] up to 1.0 mM and then levelled off (Table I). This suggests that membrane function has a minimum K requirement and increases in [K^+] above that minimum level do not improve membrane integrity.

TK increased linearly with increase in [K^+] (Table I).

TABLE II
Parameters and statistics for multiple regression models of the relationship between moisture loss (W^P) and various attributes for carrots stored at 13°C and 30% relative humidity

Variable	Full model b	Full model b'	Best model b	Best model b'
CON	91.98	—	47.98	—
[K^+]	1.08	0.31	—	—
W	−1.73	−0.97	−0.96	−0.54
ψ	−34.96	0.17	—	—
ψ_π	54.36	0.33	—	—
RSL	0.54	0.35	0.72	0.47
TK	172.72	0.16	—	—
R^2	0.81		0.81	
Cp	—		2.63	
Significance	*		*	

CON = y-intercept, [K^+] = potassium concentration in growth medium (mM), W = carrot root fresh weight (g), ψ = total water potential (MPa), ψ_π = osmotic potential (MPa), RSL = relative solute leakage, TK = K concentration in the carrot tissue (mM), Cp = Mallow's coefficient, * = significant at $P = 0.05$, b = partial regression coefficient, and b' = standard partial regression coefficient.

Stepwise multiple regression analysis

The best subset model obtained by backward stepping and the optimum Mallow's coefficient ($R^2 = 0.81$, $P \leq 0.05$, Cp. = 2.63) showed that W and RSL accounted for most of the variation in W^P (Table II). Further analysis showed a significant logarithmic relationship between W and W^P, with W^P increasing with decrease in W (Figure 1). A significant relationship between RSL and W^P with W^P increasing with increase in RSL, was found (Figure 2).

Significant ($P \leq 0.05$) linear relationships among W^P, and ψ, ψ_π, TK and [K^+], with W^P decreasing with decrease in ψ, ψ_π and with increase in TK and [K^+], were observed (data not shown). However, ψ, ψ_π, TK and [K^+] were not selected in the best subset model that explained the variation in W^P.

DISCUSSION

Moisture loss from carrot roots occurs by diffusion through the periderm and lenticels (Esau, 1965). Characteristics, including root size (Apeland and Baugerød, 1971), ψ and its components (Salisbury and Ross, 1991), and tissue integrity may affect the rate of moisture loss. This study suggests that an increase in [K^+] from 0 to 1 mM, in nutrient medium, decreases postharvest moisture loss. Backward stepping showed that W and RSL were the two independent variables which accounted for most of the variation in W^P. The W, with high standard partial regression coefficient, was more important than RSL in this regard.

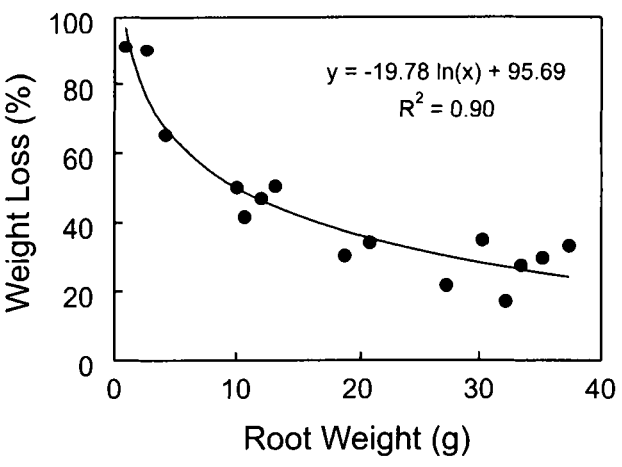

FIG. 1
The relationship between percent weight loss and fresh weight of carrot roots stored at 13°C, 30% relative humidity for 14 d.

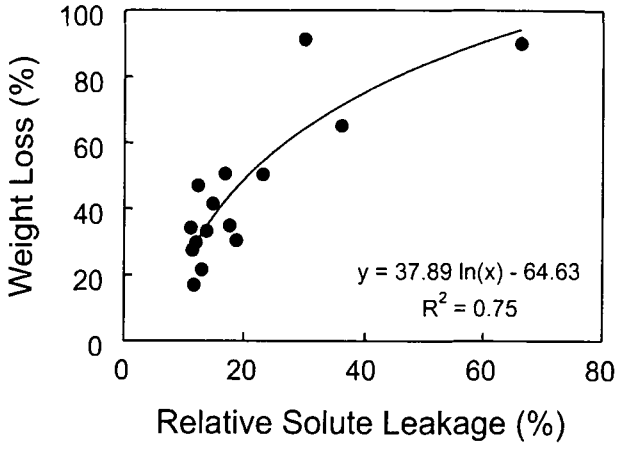

FIG. 2
The relationship between percent weight loss and relative solute leakage from carrots stored at 13°C, 30% relative humidity for 14 d.

An increase in [K^+] resulted in larger carrot roots, which in turn would reduce their surface area/volume ratio. A lower surface area/volume ratio would consequently reduce the moisture loss per unit weight of carrot. Conversely, smaller carrots, with higher surface area/volume ratios, would lose more moisture than the larger carrots.

The ease with which a plant surface allows transpiration to occur is indicated by the TC (van den Berg, 1987). Cells which offer higher resistance to water flux have lower TC. RSL has been used as an indicator of plasma membrane permeability (Pooviah and Leopold, 1976) and cellular integrity (Toivonen, 1992). The plasma membrane offers resistance to water movement, which reduces the symplastic flux (Boyer, 1985). A reduction in tissue integrity would lower this resistance and increase symplastic flux, causing the cells to lose more moisture. The high postharvest moisture loss observed in this study at low [K^+] could partly be due to an increase in the permeability of the cells to water. Interstitial and cell wall resistances may also affect transpiration (Kays, 1991). Cells with thick walls would offer greater resistance and lower the flux of water to the evaporating surfaces.

In this study, carrots grown under high [K^+] had a low ψ and lost less water. Conversely, carrots grown under low [K^+] had a high ψ and lost more moisture. However, the best subset model to explain the variation in W^P did not include ψ, suggesting that the effect of ψ on postharvest moisture loss in carrots is not as important as that of other factors.

K is required for the production of proteins and carbohydrates (Hsiao, 1976), which are necessary for plasma membrane synthesis, and for the activation and stabilization of enzymes and membranes (Wyn Jones and Pollard, 1983; Suelter, 1985). The 50 mM TK observed in the carrots grown at the highest [K^+] in this study agrees with the level of K found in cells (Glass and Siddiqi, 1984). Assuming that each K^+ is associated with an anion to maintain electrical neutrality, the increase in TK from 10 to 50 mM in this study could account for only 5.6% (0.05 MPa) and 21.1% (0.24 MPa) of the ψ_π at the lowest and the highest [K^+], respectively. This suggests that the benefits of TK were not through a lowering of ψ but through the effect on other plant functions, i.e. membrane permeability.

Potassium status of the soil has been shown to influence carrot yield response to K fertilization. For example, Bishop *et al.* (1973) observed a linear increase in the marketable yield of carrots in response to K fertilization in sphagnum peat soil, but not in mineral soil. Greenwood *et al.* (1980) observed that increasing K fertilization increased the yield of unmarketable carrots on sandy loam containing 60 ppm of K. Above this level, yield did not increase. Biegon (1995), observed no effect on K fertilization on carrot shoot growth and marketable yield in muck soil containing 503 to 693 ppm K. Carrot weight loss during short term storage was also not affected by the rate or the source of K (KCl vs. K_2SO_4). Evers (1989), on the other hand, found a negative effect of fertilization on storability of carrots. In our study, W^P, W, ψ and RSL showed response to [K^+] up to 1.0 mM, the effect levelled off thereafter. It is, therefore, suggested that K fertilization could improve the shelf life of carrots by reducing postharvest moisture loss only if the carrots are grown in soils with a very low K content.

CONCLUSION

Increased K application reduces the postharvest moisture loss in carrots during short term storage by increasing root size (weight) and by maintaining tissue integrity. The benefit of K fertilization in terms of improved shelf life, however, is limited to the conditions where there is a very low K availability.

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