Effects of Controlling pH with Hydrochloric Acid on the Growth, Yield, and Fruit Quality of Tomato Grown by Nutrient Film Technique

A.P. Papadopoulos¹ and
S. Pararajasingham²

ADDITIONAL INDEX WORDS. recirculating solution, hydroponics

SUMMARY. In growing greenhouse tomato (*Lycopersicon esculentum* Mill.) using the nutrient film technique (NFT), HNO_3 or H_3PO_4 is usually added to offset the increase in pH of the recirculating solution. For economic and environmental reasons, HCl would be a possible substitute for either HNO_3 or H_3PO_4 . Therefore, experiments were initiated to evaluate HCl as an alternative acid in controlling the pH of the recirculating solution in NFT-grown greenhouse tomato. The effects of HNO_3 , H_3PO_4 , and HCl on the growth, fruit yield, and fruit quality were quantified. In 1995, these effects were tested using 'Trust' and 'BST 7804' at a recirculating solution pH of 5.5, 6.0, or 6.5; in 1996, only 'Trust' was grown at a recirculating solution pH of 6.2. In the 1995 experiment, genotypic differences in marketable fruit yield tended to be smaller when HCl was used to control the recirculating solution pH at 6.0 than when either H_3PO_4 or HNO_3 was used. In 'Trust', at a pH of 5.5 under the HCl treatment, fruit quality tended

to be higher than in other treatment combinations. In 1996, over a 45-day period, the concentration of Cl^- that accumulated in the recirculating solution from added HCl was 313 $\text{mg}\cdot\text{L}^{-1}$ (313 ppm). There were no significant effects of the treatments on the growth, fruit quality, or yield of the crop. The total marketable yield was better when HCl had been used, likely due to high fruit production at the early part of the harvesting period. Potential savings for the season can be achieved if HCl is substituted for H_3PO_4 to regulate the nutrient solution pH in NFT-based greenhouse tomato production.

Growing greenhouse tomatoes using the nutrient film technique (NFT) involves supplying all the essential nutrients required for crop growth in the recirculating solution in adequate amounts (Winsor and Adams, 1987). As water supply is nonlimiting in NFT culture, when nutrients are taken up by the crop, the electrical conductivity (EC) of the recirculating solution declines, and, when the sole source of N is nitrates, there is a corresponding increase in solution pH (Winsor and Adams, 1987). The recirculating solution is usually replenished with nutrients from stock solutions to maintain the EC at desired levels, whereas acid, usually HNO_3 , H_3PO_4 , or both, is added to maintain the pH between 5.5 and 6.5. Controlling nutrient solution pH is essential because the pH of the root environment is a major determinant of the availability and uptake of nutrients (Adams et al., 1986). Changes in the pH of the recirculating solution are often the result of uptake of cations and anions in unequal amounts (Voogt, 1995).

Many studies suggest that tomatoes grown in NFT culture may tolerate a wide range of nutrient levels without significant loss in crop performance. Massey and Winsor (1980a) found no significant differences in the yield of tomatoes grown in NFT culture when NO_3^- -N was provided at 10 to 320 $\text{mg}\cdot\text{L}^{-1}$ (10 to 320 ppm). Similarly, yield was not affected significantly by P concentrations of 5 to 200 $\text{mg}\cdot\text{L}^{-1}$ (Massey and Winsor, 1980b). In a fertilizer formulation recommended for NFT tomatoes in soft water areas, the entire crop P requirement was supplied as KH_2PO_4 , providing P at 68 $\text{mg}\cdot\text{L}^{-1}$ of nutrient solution (Winsor et al., 1985),

thus eliminating the need for H_3PO_4 as a source of P. In this instance, HNO_3 was recommended for pH control. In a study by Richardson (1991), acids constituted 33% of the total fertilizer cost, indicating that using HNO_3 and H_3PO_4 to control pH while acting as sources of N and P, respectively, is costly. For this reason, as well as for environmental considerations, it is desirable to reduce the amount of fertilizers used in greenhouse tomato production. Therefore, attention has now shifted to HCl as a possible substitute for HNO_3 or H_3PO_4 in controlling pH in recirculating systems. Although savings for the growers are possible with HCl, its potential use as an alternative means of pH control requires investigation. Hydrochloric acid is a source of Cl^- , which probably is an essential micronutrient for higher plants (Hewitt and Watson, 1980). As such, adding HCl to a closed growing system such as NFT culture could easily cause accumulation of Cl^- in the root environment. Attenburrow and Waller (1980) found that the yield of NFT-grown tomatoes decreased 10% when 8.5 to 14.4 mM (0.067 to 0.114 oz/gal) NaCl accumulated in the circulating solution. Hand and Fussell (1995), who studied the effects of substituting KNO_3 (control) with chloride salts in circulating solution [$\text{EC} = 2800 \mu\text{S}\cdot\text{cm}^{-1}$ (2.8 $\text{mmho}\cdot\text{cm}^{-1}$)], found no differences between treatments on tomato growth, development, and yield. In a study where the effects of various ratios of NO_3^- [6 to 16 $\text{mmol}\cdot\text{L}^{-1}$ (0.051 to 0.135 oz/gal)], SO_4^{2-} [5 to 10 $\text{mmol}\cdot\text{L}^{-1}$ (0.065 to 0.131 oz/gal)], and Cl^- [3 to 13 $\text{mmol}\cdot\text{L}^{-1}$ (0.014 to 0.063 oz/gal)] were examined at a constant EC (3500 $\mu\text{S}\cdot\text{cm}^{-1}$) on tomatoes grown in a recirculating system, the number and weight of fruit per unit area and average fruit weight were found to be similar among treatments (Nukaya et al., 1991). The uptake of plant nutrients estimated by tissue analysis was unaffected by any ratio or Cl^- and SO_4^{2-} concentrations in the root environment. Hand and Fussell (1995) observed gold specks on fruit in response to elevated Cl^- levels in the root environment. Fruit with gold specks were found to be softer (Hand and Fussell, 1995). In the study by Nukaya et al. (1991), percentage of blossom-end rot (a condition induced by Ca deficiency) in fruit was 7.5% to 9.2% at the 3- $\text{mmol}\cdot\text{L}^{-1}$ (0.014 oz/gal) Cl^- treatment but was lower (5.7% to 6.9%) at the 8 to 13- $\text{mmol}\cdot\text{L}^{-1}$ (0.038 to 0.063

¹Research Scientist, Greenhouse and Processing Crops Research Centre, Agriculture and Agri-Food Canada, Harrow, Ontario, Canada N0R 1G0.

²Research Associate, Ontario Agri-Food Research Foundation, 2585 Hwy #18 East, Harrow, Ontario, Canada N0R 1G0.

The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement solely to indicate this fact.

oz/gal) Cl^- treatment. Nukaya et al. (1991) and Hand and Fussell (1995) have suggested that elevated Cl^- levels in the circulating solution enhances Ca uptake. Chloride ions in the circulating solution have no effect on the soluble solids and acid contents of tomatoes (Nukaya et al., 1991).

We studied how the growth, yield, and fruit quality of greenhouse tomato grown in NFT culture were affected by HCl compared to HNO_3 , H_3PO_4 , or both when used for pH control.

Materials and methods

EXPERIMENT 1 (SPRING 1995).

'Trust' (DeRuiter Seeds Inc., Columbus, Ohio) and 'BST 7804' ('BST') (Bruisma Seeds, Newmarket, Ontario, Canada) tomatoes were grown in a standard NFT setup in a glass greenhouse compartment [$9 \times 6.5 \text{ m}^2$ (629.5 ft^2) floor space] with environmental control where a day/night air temperature regime of $21/19^\circ\text{C}$ ($69.8/66.2^\circ\text{F}$) and a minimum relative humidity of 50% were maintained. Tomato seedlings (seventh true-leaf stage) in rockwool cubes were placed in polyethylene gullies on 6 Jan. 1995. Each gully consisted of two adjacent subplots each containing four plants of a cultivar for a total of eight plants per gully. Cultivars were allocated randomly to the subplots. Of the eight plants in each gully, six were test plants while the remaining two were the guard plants, one at each end of the gully. The plant density was 2.5 plants/ m^2 (0.23 plants/ ft^2). The treatments consisted of controlling the pH of the recirculating solution at 5.5, 6.0, or 6.5 by adding ACS grade a) (85%) H_3PO_4 , b) (70%) HNO_3 , or c) (36%) HCl diluted to 25% (v/v) for safety reasons. A single gully was used for each treatment combination for a total of nine gullies. Plants grown on rockwool slabs and placed at the outside edges of the gullies served as guard rows.

Each gully was provided with a holding tank of nutrient solution [volume 110 to 123 L (29.2 to 32.6 gal)] and a pump. A base feed was prepared by mixing stock solutions in a source tank. The EC of the recirculating solutions was maintained at the level suited for the stage of crop growth (Fig. 1) by dispensing the base feed automatically. The pH of the recirculating solution in each treatment was checked five times per week using either the Oakton pHtestr 1 (model 35624-00; Cole Parmer, Vernon Hill, Ill.) or the pHep3 (Hanna

Instruments, Woonsocket, R.I.). The EC of the recirculating solutions was checked five times per week using the Dist WP4 (Hanna Instruments). The pH was corrected by adding H_3PO_4 until 40 d after transplanting and an appropriate amount of test acid, thereafter. During the experiment, recirculating solutions were renewed three times at 46, 88, and 132 d after transplanting. The crop was topped 113 d after transplanting.

Fruit picking commenced 81 d after transplanting and continued until the end of the experiment at 196 d after transplanting. Green fruit with a red tint were picked twice weekly and graded according to Ontario commercial standards (OMAF, 1987), and the number and weight of fruit in each grade were recorded.

EXPERIMENT 2 (SPRING 1996). In this experiment, 'Trust' tomatoes were grown under conditions identical to Expt. 1. Tomato seedlings were transplanted on 21 Dec. 1995. The arrangement of plants in gullies was similar to Expt. 1 except that there were no subplots because all eight plants in a gully were of the same cultivar. The plant density was again 0.23 plants/ ft^2 . As in Expt. 1, a single gully was used for each acid treatment. The treatments in Expt. 2 consisted of controlling the recirculating solution pH at 6.2 by adding ACS grade a) (85%) H_3PO_4 , b) (70%) HNO_3 , or c) (36%) HCl, diluted to 25% (v/v) for safety reasons. The treatments were

arranged in a randomized complete-block design with three replications. Guard rows consisted of plants grown on rockwool slabs.

The composition of the recirculating solution and its supply to the crop through the NFT system was identical to that in Expt. 1. EC and pH of the recirculating solution in each treatment were checked as in Expt. 1, and the pH was corrected by adding the appropriate amount of test acid. During the experiment, recirculating solutions were renewed three times at 32, 69, and 95 d after transplanting. Twice during the season, at 53 and 143 d after transplanting at the end of the experiment, a sample of the recirculating solution [500 mL (16.9 fl oz)] was withdrawn from each treatment for chemical analysis to examine the effect of the treatments on nutrient uptake by the crop. The crop was topped 82 d after transplanting.

The following crop related measurements were made at 48, 68, and 81 d after transplanting: plant height, number of leaves and clusters, and stem diameter just below the fifth fully expanded leaf from the top. When the experiment ended, three plants from each treatment were removed, leaves

Fig. 1. Recirculating solution electrical conductivity (EC) at different growth stages of greenhouse tomato crops grown by nutrient film technique during 1995 and 1996 ($1 \mu\text{S} = 1 \mu\text{mho}$).

were counted, leaf area was measured using a leaf area meter (LI-3100; LI-COR Inc., Lincoln, Nebr.), and fresh and dry weights of leaves, stems, and roots were determined.

Fruit picking commenced 67 d after transplanting and continued until the end of the experiment. Fruit grading and recording were as in Expt. 1. Representative samples (three to four fruit) of extra large, large, or both grade fruit were allowed to ripen at ambient temperature and tested for various fruit quality measures as follows.

Fruit firmness was determined using the Ottawa texture measuring system (Voisey, 1971) by measuring the load required to just crack an intact fruit. Total ion concentration and acidity of the fruit were determined by homogenizing the fruit in a blender and measuring the EC and pH of the homogenate using Oakton pHtestr 1 testers.

All data from this experiment were subjected to analysis of variance using the ANOVA or GLM procedure of SAS (SAS Institute Inc., Cary, N.C.), and all

main effects and interactions were tested for significance. Treatment means were compared using Fischer's protected LSD procedure at $P = 0.05$ (Steel and Torrie, 1980).

Results

EXPERIMENT 1 (SPRING 1995). The overall mean cumulative marketable fruit yield in this experiment was 10.6 ± 0.26 kg (23.4 ± 0.57 lb) per plant, with yields ranging between 8.2 and 12.7 kg (18.1 and 28.1 lb) per plant (Fig. 2). The highest cumulative marketable fruit yield of 12.7 kg (28.1 lb) per plant was harvested from 'Trust' plants grown for the most part at a recirculating solution pH of 6.5 and maintained by adding H_3PO_4 , while the lowest cumulative marketable yield was harvested from plants of 'BST' grown at a pH of 6.5 using HNO_3 . At pH values 6.5 and 6.0, the final marketable fruit yield of 'Trust' was always higher than that of 'BST', regardless of acid treatments. With respect to marketable fruit yield of 'BST', at pH 6.5, the highest yield was ob-

tained from plants growing in the H_3PO_4 treatment, while at pH 6.0, plants in the HCl treatment outperformed those under the other acid treatments.

The highest percentage (64.3%) of extra large fruit was obtained from 'Trust' grown at a recirculating solution at pH 6 under the HCl treatment (Table 1). The highest percentage (100%) of grade 1 (extra large + large + small grades) fruit was obtained from 'Trust' grown at pH 5.5 using HCl for pH control (Table 1). Blossom-end rot was absent in most treatments; the highest incidence (5.0% fruit) occurred in 'BST' grown at pH 6.5 under HNO_3 . No evidence of deformed fruit (cat face) was found among any of the treatments tested.

EXPERIMENT 2 (SPRING 1996). In

Fig. 2. Effects of three acids for controlling pH on the cumulative marketable fruit weight from two cultivars of greenhouse tomato raised in nutrient film technique during 1995 (1 kg = 2.21 lb).

Table 1. Effects of three acids for controlling pH at three levels on the final proportions (%) of fruit grades from two cultivars of greenhouse tomatoes grown by nutrient film technique during 1995.

Acid treatment	Marketable fruit (%)					Unmarketable fruit (%)		
	X-large	Large	Small	Commercial	Grade 2	Cat face	BER	Waste fruit
Trust (pH 6.5)								
Phosphoric acid	41.2	49.2	6.1	0.9	0.0	0	2.6	0
Nitric acid	34.9	47.8	3.5	1.4	8.4	0	4.0	0
Hydrochloric acid	49.0	39.6	8.4	0.4	2.0	0	0.6	0
BST 7804 (pH 6.5)								
Phosphoric acid	49.7	45.6	0.0	0.0	4.7	0	0	0
Nitric acid	32.6	54.6	2.6	0.0	5.2	0	5.0	0
Hydrochloric acid	40.2	55.1	0.4	0.0	4.3	0	0.0	0
Trust (pH 6.0)								
Phosphoric acid	50.9	45.3	0.3	0.5	3.1	0	0.0	0
Nitric acid	49.6	41.1	4.6	0.6	4.1	0	0.0	0
Hydrochloric acid	64.3	31.3	2.3	0.0	2.1	0	0.0	0
BST 7804 (pH 6.0)								
Phosphoric acid	34.1	58.3	2.1	0.0	5.0	0	0.5	0
Nitric acid	30.8	55.0	5.6	0.0	8.5	0	0.0	0
Hydrochloric acid	49.1	45.6	0.2	0.4	4.7	0	0.0	0
Trust (pH 5.5)								
Phosphoric acid	40.0	46.9	3.4	0.0	5.9	0	3.8	0
Nitric acid	44.5	44.6	5.0	0.0	4.4	0	1.4	0
Hydrochloric acid	51.3	48.2	0.5	0.0	0.0	0	0.0	0
BST 7804 (pH 5.5)								
Phosphoric acid	39.1	57.7	1.6	0.2	1.4	0	0.0	0
Nitric acid	38.0	48.5	8.0	0.0	5.5	0	0.0	0
Hydrochloric acid	41.1	54.7	0.6	0.0	3.5	0	0.0	0

a cropping season that spanned 20 weeks from transplanting to final harvest, the total volumes of (85%) H_3PO_4 , (70%) HNO_3 , and (36%) HCl (diluted to a uniform 25% by volume for safety) required to regulate the nutrient solution pH in the respective treatments, on average, were 164.3, 185.6, and 249.9 $\text{mL}\cdot\text{m}^{-2}$ (176.3, 199.1, and 268.1 gal/acre). At horticultural-grade prices, acid costs for pH control in the H_3PO_4 , HNO_3 , and HCl treatments amounted to US \$579, \$447, and \$311 per hectare (\$231, \$178, and \$124 per acre), respectively.

Over a 3-week period beginning in January ($\text{EC } 2800 \mu\text{S}\cdot\text{cm}^{-1}$), using HCl for pH control was calculated to raise the Cl^- concentration in the recirculat-

ing solution, on an average, to a value of $73.0 \text{ mg}\cdot\text{L}^{-1}$ up from the $11 \text{ mg}\cdot\text{L}^{-1}$ found in tap water. At the end of this period, the measured mean Cl^- concentration (minus the Cl^- in water) in the recirculating solution was $49 \text{ mg}\cdot\text{L}^{-1}$. In a subsequent 45-d period beginning in late March ($\text{EC } 2600 \mu\text{S}\cdot\text{cm}^{-1}$), the added HCl supplied an average of $371 \text{ mg}\cdot\text{L}^{-1}$ of Cl^- to the recirculating solution, 34-fold more than in tap water. The measured mean Cl^- concentration indicated that $313 \text{ mg}\cdot\text{L}^{-1}$ of Cl^- accumulated in the recirculating solution during this period. Chloride uptake, calculated as a percentage of the amount disappeared from that supplied in the recirculating solution for the two periods in question, was 21% and 16%,

respectively.

Crop growth measured as plant height, leaf and cluster numbers, and stem diameter on three occasions before topping the crop was unaffected by the treatments (Table 2); neither were the final leaf area and biomass of plant parts (Table 3).

After 10 weeks of harvesting, the highest marketable yield was achieved when HCl was used to control the pH in the recirculating solution (Fig. 3). In plants grown under the HCl treatment, the mean rate of fresh weight accumulation was $74 \pm 3 \text{ g}\cdot\text{d}^{-1}$ ($2.6 \pm 0.11 \text{ oz/d}$) for a total marketable fruit weight of $4.9 \pm 0.35 \text{ kg/plant}$ ($10.8 \pm 0.77 \text{ lb/plant}$). Using H_3PO_4 to control pH depressed the total marketable yield. In

Table 2. Effects of three acids for pH control on crop growth before topping in a greenhouse tomato crop grown by nutrient film technique during 1996. Each value is the mean of nine observations $\pm$ SE.

Crop growth parameter	Crop age (d)								
	48			68			81		
	H_3PO_4	HNO_3	HCl	H_3PO_4	HNO_3	HCl	H_3PO_4	HNO_3	HCl
Height (cm) ²	169 ± 2.4	163 ± 3.7	167 ± 1.5	216 ± 2.4	213 ± 4.6	213 ± 3.7	248 ± 1.5	247 ± 5.6	239 ± 7.8
Leaf no.	19.9 ± 0.76	19.2 ± 0.47	19.7 ± 0.49	22.2 ± 0.39	21.7 ± 0.69	22.6 ± 0.72	26.8 ± 1.8	25.3 ± 2.0	25.3 ± 1.4
Cluster no.	6.1 ± 0.1	6.5 ± 0.23	6.4 ± 0.29	7.6 ± 0.47	7.8 ± 0.29	7.6 ± 0.33	9.5 ± 0.23	9.2 ± 0.39	9.1 ± 0.29
Diameter (mm) ²	13.4 ± 1.2	13.4 ± 0.94	12.9 ± 0.92	11.7 ± 0.33	11.5 ± 0.39	11.3 ± 0.20	11.5 ± 0.39	11.9 ± 1.1	11.3 ± 0.69

²1 cm = 0.394 inch; 1 mm = 0.0394 inch

Table 3. Effects of three acids for pH control on leaf area and crop biomass at final harvest in a greenhouse tomato crop grown by nutrient film technique during 1996. Each value is the mean of nine observations $\pm$ SE.

Treatment	Leaf area (cm ² /plant) ^a	Leaf	Stem biomass (g plant ⁻¹) ^a	Root
Phosphoric acid	898 $\pm$ 70.6	128 $\pm$ 19.5	55.4 $\pm$ 3.5	65.5 $\pm$ 6.0
Nitric acid	866 $\pm$ 85.0	122 $\pm$ 13.7	54.7 $\pm$ 5.3	53.9 $\pm$ 5.1
Hydrochloric acid	765 $\pm$ 72.0	132 $\pm$ 5.4	58.8 $\pm$ 1.3	56.6 $\pm$ 0.9

^a 1 cm² = 0.155 inch²; 1 g = 0.002 lb.

these plants, a mean rate of 67 ± 3 g·d⁻¹ (2.4 ± 0.11 oz/d) fresh weight resulted in a total marketable yield of 4.4 ± 0.1 kg/plant (9.7 ± 0.22 lb/plant) at the end of experiment. The effect of the treatments on the cropping pattern was of considerable interest. During the first 4 weeks of picking, the average marketable yield was identical between plants receiving the HCl and H₃PO₄ treatments but was significantly higher than those grown in the HNO₃ treatment ($p < 0.001$). Plants in the HCl treatment outperformed plants in the other two treatments in total marketable yield in 8 of the 10 weeks (Fig. 3), while the plants receiving HNO₃ produced the least marketable yield. Beginning week 7 of the harvesting period, the difference in total marketable yield between the HCl and HNO₃ treatments became smaller (Fig. 3). The increase in the rate of fruit weight accumulation at the final harvest was the result of picking all the remain-

ing fruit, including the green ones, when the experiment ended.

The effect of acid treatments on cumulative fruit number generally was similar to that on fruit weight (Fig. 4). After 10 weeks of harvest, total fruit number per plant was highest in the HCl treatment at 32.9 ± 2.1 fruit/plant. Cumulative fruit number in the HNO₃ treatment was markedly lower during the first eight pickings compared to the HCl treatment, but it increased in the final seven pickings to result in identical fruit numbers in all the treatments by the end of the experiment. The rise in fruit production rate during the final interval (Fig. 4) was again the result of strip harvesting the fruit at the end of the experiment.

The proportion of marketable fruit weight as a percentage of total fruit weight over the 10 weeks of harvest did not differ significantly among treatments (Table 4). A breakdown of marketable fruit into grade 1, grade 2, and commercial grades indicated that the treatments had no effect on fruit size. In this experiment, no incidence of blossom-end rot was evident under any of the treatments tested.

Other measures of fruit quality, fruit firmness and the total ion concentration and acidity of the homogenized fruit did not differ significantly among the three acids tested (Table 5).

Discussion

We have demonstrated that it is possible to grow greenhouse tomato in NFT systems using HCl to control the pH of the recirculating solution

without adverse effects on crop growth, fruit yield, and quality provided adequate nutrients are supplied, proper EC is maintained, and the recirculating solution renewed periodically. Genotypic differences in fresh weight accumulation rate tend to be small when using HCl provided the recirculating solution pH is kept at 6.0 (Fig. 2).

The maximum Cl⁻ concentration in the root environment for tomato grown in NFT without risking toxicity has been reported to vary between 200 (Richardson, 1991) and 400 mg·L⁻¹ (Adams and Bailey-Anguish, 1988). At no time in this experiment did Cl⁻ in the recirculating solution exceed the upper limit of the concentration that may be considered damaging. However, work by Adams and Bailey-Anguish (1988) and Nukaya et al. (1991) indicated that greenhouse tomato may tolerate Cl⁻ concentrations in the root environment up to 750 mg·L⁻¹ and benefit positively from such moderate concentrations in terms of marketable fruit yield and quality of the fruit. Hand and Fussell (1995) observed that increasing the Cl⁻ concentration from 150 to 600 mg·L⁻¹ enhanced gold spot incidence on greenhouse tomato, although plant growth and yield were not significantly affected by the treatments. Irrespective of Cl⁻ levels in the root zone, blossom-end rot was absent in our experiment. Accord-

Fig. 4. Effects of three acids for controlling pH on the cumulative marketable fruit number of a greenhouse tomato crop raised by nutrient film technique during 1996 (1 kg = 2.21 lb).

Table 4. Effects of three acids for pH control on the final proportions (%) of fruit grades from a greenhouse tomato crop grown by nutrient film technique during 1996.

Treatment	Marketable fruit (%)					Unmarketable fruit (%)		
	Grade 1		Small	Commercial	Grade 2	Cat face	BER	Waste fruit
	X large	Large						
Phosphoric acid	20.9	27.1	11.4	9.8	17.3	3.1	0	10.5
Nitric acid	22.2	28.1	11.2	4.1	18.2	6.1	0	10.2
Hydrochloric acid	23.8	28.5	12.6	8.2	19.6	3.1	0	4.3

Table 5. Effects of three acids for pH control on some fruit quality measures of ripe fruits from a greenhouse tomato crop grown by nutrient film technique during 1996. Each value is an average of number of measurements $\pm$ SE.

Treatment	Fruit firmness (N·mm ⁻²) ^y	EC ^x (μ S·cm ⁻¹) ^y	pH
Phosphoric acid	8.0 $\pm$ 0.45	3791 $\pm$ 72	4.6 $\pm$ 0.01
Nitric acid	7.8 $\pm$ 0.34	3696 $\pm$ 167	4.6 $\pm$ 0.01
Hydrochloric acid	8.4 $\pm$ 0.49	3834 $\pm$ 222	4.6 $\pm$ 0.01

^xEC = total ion concentration of harvested fruits measured as electrical conductivity.

^y1 N mm⁻² = 10 bar = 145 lb/inch².

ing to Willumsen et al. (1996), blossom-end rot is not affected by a single factor but by the interaction of many factors, examples of which are salinity and nutrient ratios in the root zone, daily solar radiation, air temperature, and air humidity.

Of the two estimates for Cl⁻ uptake rates at different periods in the season, the high rate coincided with the period when solution EC was maintained at a high level (2800 μ S·cm⁻¹) to promote flowering. In view of the positive responses of the crop to added HCl, to help reduce fertilizer costs it would be interesting to determine how the crop would perform if the solution EC was achieved by elevated Cl⁻ supply.

Using HCl to control pH in this NFT experiment resulted in an increase in marketable fruit yield (up to 14% over the H₃PO₄ treatment in Expt. 2) with no appreciable changes in fruit quality. From the beginning of the harvesting period, plants raised under the HCl treatment at pH 6.2 consistently produced higher marketable yields compared to the other treatments, indicating that Cl⁻ in the recirculating solution helped boost fruit production early in the season, thereby establishing a favorable improvement in productivity throughout the season. However, depending on the genotype, growing greenhouse tomato using H₃PO₄ to control the recirculating solution pH at 6.5 would result in high yields of mod-

est quality fruit so that high market prices for the crop can be realized (Fig. 2, Table 1). Against this beneficial effect must be set the higher cost associated with using H₃PO₄ to control pH compared to the other test acids. We conclude that greenhouse tomato growers who rely on NFT cropping systems to raise their crop are better off using HCl rather than other acids, especially H₃PO₄, for controlling the recirculating solution pH because HCl in the root zone appears to influence greenhouse tomato yield favorably. The mechanism of the beneficial effects of added HCl on greenhouse tomato yield awaits further investigation.

Literature cited

- Adams, P., C. J. Graves, and G. W. Winsor. 1986. Some effects of micro nutrients and liming on the yield, quality and micronutrient status of lettuce grown in beds of peat. *J. Hort. Sci.* 61:515-521.
- Adams, P. and M. Bailey-Anguish. 1988. Some responses of tomato to sodium chloride. *Annu. Rpt. 1986-1987, Glasshouse Crops Res. Inst., Littlehampton, Sussex, U.K.*
- Attenburrow, D.C. and P. L. Waller. 1980. Sodium chloride: Its effect on nutrient uptake and crop yields with tomatoes in NFT. *Acta Hort.* 98:229-236.
- Hand, D.J. and M. Fussell. 1995. The effect of reduced nitrate input on tomato yield and fruit quality. *Acta Hort.* 401:319-325.
- Hewitt, E.J. and E.F. Watson. 1980. The production of micronutrient element deficiencies in plants grown in recirculated nutrient film (NFT) systems. *Acta Hort.* 98:179-185.
- Massey, D.M. and G.W. Winsor. 1980a. Some responses of tomato to nitrogen in recirculating solutions. *Acta Hort.* 98:127-137.
- Massey, D.M. and G.W. Winsor. 1980b. Some response of tomato plants to phosphorus concentration in nutrient film culture. *Proc. 5th Intl. Congr. Soilless Culture, Wageningen, The Netherlands.* p. 205-214.
- Nukaya, A., W. Voogt, and C. Sonneveld. 1991. Effects of NO₃, SO₄ and Cl ratios on tomatoes grown in recirculating system. *Acta Hort.* 294:297-304.
- OMAF. 1987. Greenhouse tomato grading and packing manual. Fruit and Veg. Inspection Branch, Ontario Min. of Agr. and Food, Ontario, Canada.
- Richardson, S. 1991. Hydroponics and nutrient film culture, p. 353-374. In: D.A. Palgrave (ed.). *Fluid fertilizer science and technology*. Dekker, New York.
- Steel, R.G.D. and J.H. Torrie. 1980. *Principles and procedures of statistics*. McGraw-Hill, New York.
- Voisey, P.W. 1971. The Ottawa texture measuring system. *J. Can. Inst. Food Technol.* 4:91-103.
- Voogt, W. 1995. Effect of the pH on rock-wool grown carnation (*Dianthus caryophyllus*). *Acta Hort.* 401:327-336.
- Willumsen, J., K.K. Petersen, and K. Kaack. 1996. Yield and blossom-end rot of tomato as affected by salinity and cation activity ratios in the root zone. *J. Hort. Sci.* 71:81-98.
- Winsor, G.W., R.G. Hurd, and D. Price. 1985. Nutrient film technique. *Growers' Bul. No. 5*, 2nd ed., Glasshouse Crops Res. Inst., Littlehampton, U.K.
- Winsor G. and P. Adams. 1987. *Glasshouse crops. vol. 3. Diagnosis of mineral disorders in plants*. Her Majesty's Stationery Office, London, U.K.