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Effects of Phosphorus Fertilizer Supplementation on Processing Quality and Functional Food Ingredients in Tomato

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Even though several types of phosphorus fertilizers are used in crop production, the influence of phosphorus on produce quality is not well understood. Several quality attributes of tomato juice were analyzed in relation to phosphorus supplementation during a three-year field study (2000−2002). In addition to the recommended phosphorus fertilization, phosphorus supplementations, either through soil (low and high) or through foliar spray (hydrophos, seniphos), were tested. In general, soil and foliar phosphorus supplementation did not provide a statistically significant increase in yield. Tomato juice was evaluated for various quality characteristics including pH, titratable acidity, precipitate weight ratio, total solids, serum viscosity, Brookfield viscosity, color, lycopene levels, vitamin C, and flavor volatiles. Changes observed in several quality parameters were marginal, statistically insignificant and influenced by the season. Therefore, it appears that phosphorus supplementation may not significantly affect the processing quality parameters in tomato fruits.

KEYWORDS: Flavor volatiles; lycopene; *Lycopersicon esculentum*; nutraceuticals; processing quality; juice viscosity

INTRODUCTION

Methods for the production of fruits and vegetables of optimal quality involve constantly changing strategies that incorporate the increased understanding of the sciences of production, food quality, nutritional values, and health beneficial roles. The current methods of fruit and vegetable production use fertilizer application regimes that were recommended mostly on the basis of obtaining maximum volume or weight of the produce, and do not consider the finer aspects of quality. Phosphorus is a key component in the metabolism and regulates the operation of several pathways involved in the biosynthesis of secondary plant products, many of which are nutraceuticals. However, phosphorus fertilizer application is not recommended for fruit crops, on the ground that, there is adequate soil phosphorus required for a complete fruit production cycle (*1*). In this study, we have evaluated the effects of soil and foliar application of phosphorus on the nutritional and processing qualities of tomatoes. Increasing the nutritional quality of tomato can increase the value of the produce, thus helping the growers and processing industries alike.

In recent years, there is considerable interest in enhancing the yield as well as nutritional quality of fruits and vegetables (*2*). Previous studies have shown that application of potassium fertilizers can enhance the levels of carotenoids in tomato, especially lycopene (*3*). Wright and Harris (*4*) found that the total acidity of tomato is also increased by nitrogen in soil. Because of the key metabolic role of phosphorus in the biosynthesis of nutritionally important components which determine the quality of the produce, phosphorus may play an equal or more important role in providing the best combination of organoleptic and nutritional qualities. To date, no detailed studies have been conducted to evaluate the effect and role of phosphorus nutrition on the levels of functional food ingredients (nutraceuticals), and quality in any fruits or vegetables.

An appropriate level of phosphorus nutrition is crucial not only for the normal growth and development of the plants, but also for the synthesis of several metabolic intermediates. This is primarily because the energy for biosynthetic reactions comes from adenosine triphosphate (ATP) and the reducing power comes through the reduced form of nicotinamide adenine dinucleotide phosphate ($NADPH_2$), both being phosphorus-containing compounds. Inorganic phosphate is absorbed from the soil solution and transported into the cells through the activities of phosphate transporters (*5*). In tomato, there are high affinity and low affinity transporters, and the high affinity transporters are induced under phosphate starvation (*6*, *7*). In addition to the roots, the phosphate transporters are present in leaves. Expression and levels of leaf phosphate transporters may become important in the absorption and assimilation of foliar-applied phosphorus. Biosynthesis of lycopene, carotene, tocopherols, quinones, various terpenes, etc. is achieved through the activity of isoprenoid pathway, that utilize pyrophosphates, ATP

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and NADPH (*8*). The flavonoids and phenolic components are derived from the pentose phosphate pathway (PPP), which is a key metabolic pathway in plants (*8*). PPP is involved in the maintenance and proper functioning of the antioxidant defense system, that is critical to attaining stress tolerance in plants and their produce (*9*). Thus, phosphorus may indirectly affect the quality parameters through the regulation of biosynthesis of several ingredients.

MATERIALS AND METHODS

Tomato. Tomato seeds (*Lycopersicon esculentum* Mill. H 9478), a Heinz processing variety, were germinated in potting soil in the greenhouse. Four-week-old plants were transplanted into the field in early June 2000, 2001, and 2002 at the Cambridge Research Station of the University of Guelph. Tomato seedlings were planted in plots of 1.8 × 3 m, each plot containing 24 plants. Each plot was separated from the others by a minimum distance of 1.5 m. All soil fertilizer applications were conducted for the plots as per the Ontario Ministry of Agriculture and Food (OMAF) recommendations (250 kg of 5:20:20 [N:P:K] per hectare that provides 50 kg of P_20_5 per hectare (ha) for soils containing 30 to 50 mg/L available phosphorus). The regular phosphorus plots (RP, receiving OMAF-recommended dose) received 135 g of 5:20:20 and 80 g of ammonium nitrate (40:0:0) at the time of planting. The low phosphorus-supplemented plots (LP) received an additional 315 g of superphosphate (0:20:0, equivalent to approximately 111 kg total P_20_5/ha), and the high phosphorus-supplemented plots (HP) received 630 g of superphosphate (approximately 222 kg total P_20_5/ha). Phosphorus supplementation was also performed through foliar sprays of Hydrophos (300 mL in 64 L, 4 L per plot) and Seniphos (600 mL in 64 L, 4 L per plot) twice at 15-day intervals after completion of blooming. Hydrophos contained high analysis phosphorus 0−29−5 with magnesium (P_20_5—29% w/v, Mg^{2+}—4% w/v and K_2O—5% w/v), and seniphos contained high analysis phosphorus 3−24−0 with calcium (P_20_5—24% w/v, and Ca^{2+}—3% w/v). Both are products of Phosyn PLC, UK. These plots received 135 g of 5:20:20 and 80 g of ammonium nitrate per plot as in RP treatment. During 2001 and 2002 seasons, an additional control was included where no phosphorus was added [NP, 80 g of ammonium nitrate and 60 g potash (0:0:60) per plot]. In 2001, a combination of treatments (COMB) including LP, Hydrophos, and Seniphos was also included. There were four randomly selected replicates for each treatment.

Yield. The yield was calculated using the total amount of 5 consecutive harvests in the first year and 3 harvests in the second and third year. Ripe tomatoes from each plot were harvested and weighed. The values (MT, metric ton) were extrapolated to a per hectare basis.

Phosphorus Content. Phosphorus contents of tomato samples were determined by a colorimetric assay (*10*). Two grams of blended tomato were ashed at 600 °C for 4 h in an oven, cooled and digested with 5 mL of 6N HCl and several drops of nitric acid till complete dissolution of the ash. The solution was cooled and diluted to 100 mL with distilled water in a volumetric flask. One-half mL aliquots were transferred to test tubes and diluted with 9.5 mL of water. One mL of Molybdo-vanadate reagent was added and the absorbance was measured at 710 nm after 10 min. For the preparation of molybdovanadate reagent, 25 mL of sulfuric acid (2.6 mol·L^{-1}) was mixed with 10 mL of ammonium molybdate solution (50 g·L^{-1}), 10 mL of ascorbic acid solution (50 g·L^{-1}) and 5 mL of potassium antimony tartarate solution (3 g·L^{-1}), in a 100 mL separatory funnel. Ten mL of iso-butanol was added and shaken for 1 min. The solution was left in the darkness, and after 30 min the organic layer was discarded. The mixture was prepared daily. A standard curve was generated according to the AOAC method (*11*) using known amounts of potassium phosphate.

Analysis of Processing Qualities. For hot-break processing, 3 kg of tomato from each replicate was carefully washed and blanched for 1min in boiling water. The skin and seeds were removed, and the pulp blended at high speed in an Osterizer blender for 3 min followed by 1-min homogenization (*12*). The juice obtained was then quickly brought to boil and held at the boiling point for 1 min. The juice was hot canned and retorted in 500 mL mason jars using a Lagostina cooker at 111.7 °C and 0.55 bar pressure for 35 min (*13*, *14*), and cooled in ice water. The juice processed in this way was used for determining the viscosity, precipitate weight ratio, density, serum separation, and sensory evaluation for thickness. For cold break processing, 1 kg of randomly chosen frozen tomato of each replicate was thawed in closed plastic bags with running water. They were then blended for 3 min at a high speed using an Osterizer blender. The seeds and skins were removed using a strainer, and the juice was homogenized for 1 min with a Polytron homogenizer before heating at 82 °C for 1 min. These samples were used for lycopene, color, pH, acidity and ash content determination (*14*). The samples were stored in a cold room at 4−6 °C.

Measurements of Physicochemical Parameters. The Brookfield viscosity of tomato juice was measured with a Brookfield viscometer, springle # 4 at 10 rpm and only the 10th round readings were recorded (*15*). The Serum viscosity (SV) was measured with a Cannon-Fenske viscometer (size # 50), a modification of Ostwald viscometers for transparent liquids, at 25 °C and 20 °C (*16*, *17*). The serum was obtained by centrifugation of the juice sample at 12800*g* for 30 min at 4 °C followed by filtration of the supernatant through Whatman # 1 filter paper. Seven mL of filtered serum was used for the measurement of viscosity (*17*). The flow time was recorded and the density was measured at the same temperature according to AOAC's official method (*11*). The kinematic viscosity (ν) is expressed in centistokes (cSt or mm^2/s) and calculated as follows

$$\nu = Ct$$

where C = calibration constant of the viscometer, cSt/s and t = flow time, s.

The dynamic viscosity is calculated as follows

$$\eta = \rho\nu$$

where η = dynamic viscosity, centipoise (cP) or millipascal-second (mPa.s), ρ = density, g/mL, at the same temperature used for measuring the flow time t, and ν = kinematic viscosity, cSt (mm^2/s).

For determining precipitate weight ratio, approximately 40 g of tomato juice samples prepared through hot break process, were accurately weighed into 50 mL preweighed glass centrifuge tubes. The samples were centrifuged at 12 800 × *g*, for 30 min at 4 °C. After centrifugation, the supernatant was removed from the precipitate (*18*). The precipitate with the tube was then reweighed accurately and the precipitate weight ratio was calculated by using the equation

$$\text{PWR\%} = \frac{(\text{precipitate} + \text{tube weight}) - (\text{tube weight})}{(\text{initial sample} + \text{tube weight}) - (\text{tube weight})} \times 100$$

The pH of all samples was measured at room temperature with a pH meter (Fisher Scientific Company, Mississauga, Ontario).

The soluble solids contents of all samples were measured at room temperature with a hand held refractometer, Fisherbrand, 0−25%, (Fisher Scientific Company). Readings were expressed as degree Brix (AOAC Method 9.32.14C) (*11*).

For determining total acidity, 10 g of tomato juice was accurately weighed into 250 mL beakers in duplicate. To each sample 200 mL of distilled water was added. The resulting mixture was titrated with 0.1 N NaOH to a pH value of 8.0 in an Accumet Basic AB15−pH meter (Fisher Scientific Company). Total acidity was calculated as percentage of citric acid on a fresh weight basis (*11*, *19*, *20*).

For determining ash content, 10 g of tomato juice was accurately weighed in predried crucibles. The samples were ashed for 16 h in an Isotemp muffle furnace (Fisherbrand) at 550 °C. The ash content was calculated using the following formula (AOAC International, 900.02A) (*11*)

$$\%\ \text{ash (dry basis)} = \frac{(\text{weight after ashing} - \text{weight of crucible})}{(\text{original sample weight}) \times (\text{dry matter coefficient})} \times 100$$

where dry matter coefficient = % solids/100 g of juice.

The moisture and total solids contents were measured and calculated according to AOAC Method 926.08 (*11*).

Vitamin C was analyzed by the 2,6-dichloroindophenol titration, AOAC Method 967.21,45.1.14 modified by Pelletier (*21*).

Color. Tomato juice processed using a cold break procedure was analyzed using a Minolta CR-300 Chroma Meter (Minolta, Ramsey, NJ) calibrated with a white standard tile ($L = 97.1$, $a+ = 0.29$ and $b+ = 1.82$). One hundred mL of each replicate was transferred to beakers and the color measurements were performed on the surface of the liquid 5 times at different places. The chromaticity parameters *L*, *a*, *b*, *a*/*b* and hue recorded were the average of five measurements for each replicate (*22*).

Lycopene. Tomato juice, 4 g, with 8.9° Brix, was precisely weighed into 250 mL brown bottles to exclude light (*23*). One hundred mL of hexane:acetone:ethanol (2:1:1 v/v) was added to each bottle, closed and agitated for 10 min on a wrist action shaker (Burrell Corp., Pittsburgh, PA). This was followed by the addition of 15 mL of water and further shaking for 5 min. The solution separated into a distinct aqueous layer (65 mL) and an organic layer (50 mL). The organic phase was removed and filtered with 0.45 μm nylon membrane filter (Fisher Scientific Co.). Fifty μL of the filtered aliquot was subjected to HPLC analysis using a Waters 600S system on an Exterra C18 column with acetonitrile:methanol (85:15 v/v, solvent A) and methanol:hexane (75:25 v/v solvent B). The elution was started with 100% of solvent A and 0% of solvent B at time 0 and ended with 100% of solvent B, and 0% of solvent A, in a linear gradient for a period of 10 min. The elution of β-Carotene and lycopene was monitored at 475 nm. The lycopene standard used was 95% pure (Sigma Chemical Co.) and showed a retention time of 3.88 min.

Flavor Volatiles. Volatile compounds emanating from the processed tomato juice were allowed to adsorb on to a microprobe of a solid-phase micro-extraction (SPME) injection unit (Supelco, Mississauga, Ontario, Canada). Approximately 10 g of juice sample was kept in 16 $\times$ 150 mm glass tube and closed airtight with a serum vial stopper. After 30 min of incubation at room temperature, the SPME probe (100 μm in diameter, coated with poly(dimethylsiloxane)) was introduced into the tube and headspace volatiles allowed to adsorb for a period of 20 min (*24*). Desorption of the compounds from the probe was achieved in the injector of a Saturn 2000R GC−MS system (Varian) at 275 °C for 2 min. The oven temperature was increased from 50 °C to 220 °C at a rate of 10 °C min^{-1} and held constant for 10 min. Helium was used as the carrier gas at a flow rate of 1 mL min^{-1}. Ionization of the eluted compounds was achieved by electron impact in auto ion control mode. Spectra were acquired constantly with a total acquisition time of 27 min. Volatiles were identified by library search and comparison to stored spectra of authentic compounds. Volatile analysis was replicated 4 times.

Statistical Analysis. The experiment involved five treatments including regular phosphorus, low phosphorus, high phosphorus, hydrophos, and seniphos during the first year. In the second and third year, additional replicates without added phosphorus (NP) were included in a completely randomized design. The data were tested statistically by analysis of variance using the General Linear Models (Proc GLM, of SAS Institute Inc., Cary, NC, version 8e). Trends were considered significant, when means of compared sets differed at $p = 0.05$ level of significance. All experiments were replicated 4 times and the results shown are the mean ± SD from the four replicates.

RESULTS

In this study, the effect of phosphorus supplementation on quality parameters of tomato fruits and its processed products were investigated during three seasons. Climatic variation can have a tremendous influence on the qualities of fruits and vegetables and therefore, a single season study may not entirely provide a clear picture on these quality parameters. The 2000 season was very wet, with very few sunny days, the 2001 season was extremely hot and dry, and the 2002 season was nearly ideal for the growth of tomatoes. The 2000 season had increased loss of fruits due to damage and pathogen infection, the yields were low in 2001 and above average in 2002. The quality parameters were also different during these seasons. However, some general patterns resulting from phosphorus supplementation can be deciphered in tomato fruit quality and yield.

Table 1. Effect of Phosphorus Supplementation on the Yield of Tomatoes during the Seasons of Study[a]

	yield, metric tons/hectare		
treatment	2000	2001	2002
NP	ND[b]	64 ± 10a	212 ± 33a
RP	97 ± 3a	101 ± 8a	180 ± 42a
LP	91 ± 7a	97 ± 15a	179 ± 43a
HP	112 ± 6a	ND[b]	197 ± 37a
HYDRO	101 ± 5a	84 ± 8a	199 ± 33a
SENI	91 ± 4a	79 ± 7a	195 ± 33a
COMB	ND[b]	79 ± 3a	ND[b]

[a] Statistically significant ($p < 0.05$) values are designated by different letters. [b] ND, not determined.

Table 2. Effect of Phosphorus Supplementation on Fruit Weight[a]

	fruit weight, g		
treatment	green	orange	red
NP	29.72 ± 5.89a	42.32 ± 13.35a	42.31 ± 14.42a
RP	27.39 ± 2.90a	39.02 ± 5.23a	43.76 ± 8.17a
LP	29.15 ± 2.68a	37.54 ± 5.56a	42.63 ± 9.81a
HP	ND[b]	ND[b]	ND[b]
HYDRO	26.52 ± 2.25a	40.89 ± 8.67a	47.97 ± 5.90a
SENI	27.09 ± 3.18a	38.52 ± 11.56a	45.16 ± 10.22a
COMB	29.17 ± 1.88a	43.74 ± 6.22a	48.53 ± 2.90a

[a] The measurements were made during the 2001 season. Statistically significant ($p < 0.05$) values are designated by different letters. [b] ND, not determined.

Effect of Phosphorus Supplementation on Yield. Phosphorus supplementation had an initial effect on the vegetative growth of plants. At early stages, tomato plants in plots supplemented with high phosphorus showed enhanced growth and better filling of the plots. The plants provided with regular phosphorus fertilization, low level of phosphorus supplementation, hydrophos, and seniphos treatments were very similar. At later stages of growth, no morphological differences could be noticed between any of the treatments. The yield was calculated by adding the total weight of harvested tomatoes from four plots for each treatment. The yield was comparable in 2000 and 2001 season, which were in the range of 80 to 100 MT/ha. Phosphorus supplementation does not appear to have caused a statistically significant increase in the yield during any season (**Table 1**).

Phosphorus supplementation did not appear to affect the fruit weight as well. In general, the plots provided with foliar supplementation as hydrophos provided the best quality fruits as judged by their appearance. The differences in fruit weight observed in all treatments and during different seasons were not statistically significant (**Table 2**).

Physicochemical Properties of Juice. The phosphorus content of tomato juice varied significantly between treatments only during the 2000 season (**Table 3**). During the 2000 season, juice prepared from tomatoes of low phosphorus and high phosphorus supplemented plots showed an increase in phosphorus content. Phosphorus content of juice from tomatoes of regular phosphorus plots was 216.5 mg kg^{-1} wet weight, and the phosphorus content increased to 293.5 mg kg^{-1} wet weight in juice prepared from low phosphorus supplemented plots, and to 377.9 mg kg^{-1} wet weight in juice prepared from tomatoes of high phosphorus supplemented plots (**Table 3**). There were no major differences in the juice phosphorus content during 2001

Table 3. Phosphorus Content of Tomato Juice from Fruits Harvested during 2000, 2001 and 2002 Seasons[a]

	phosphorus content, mg·Kg^{-1}		
treatment	2000	2001	2002
NP	ND[b]	236 ± 46a	1036 ± 157a
RP	216 ± 12b	221 ± 31a	1084 ± 59a
LP	293 ± 20ba	244 ± 70a	1149 ± 278a
HP	378 ± 25a	ND[b]	1135 ± 161a
HYDRO	174 ± 63b	217 ± 32a	1019 ± 109a
SENI	192 ± 57b	233 ± 45a	1103 ± 99a
COMB	ND[b]	283 ± 63a	ND[b]

[a] Statistically significant ($p < 0.05$) values are designated by different letters. [b] ND, not determined.

and 2002 seasons between various treatments. Interestingly, the juice prepared from tomatoes harvested during the 2002 season had nearly 3−4 times higher levels of phosphorus as compared to that from earlier seasons (**Table 3**). The other quality parameters for juice such as °Brix, acidity, pH, ash content, total solids (TS) and vitamin C levels did not show significant differences between treatments, and were nearly similar during different seasons (**Tables 4**−**6**).

Color Analysis. Red color is the most important quality attribute of tomato and tomato products. The color parameters (L, brightness; a^+, red; b^+, yellow) of tomato juice prepared from fruits of different phosphorus treatment sets were measured using a Minolta colorimeter. The stability of the red color is expressed through a/b ratio, which is the ratio between the relative intensities of the red (lycopene) and yellow (carotene) pigments. The higher this ratio, the better the quality of the processed product. There were no major noticeable differences in the color parameters of tomato juice during the three seasons or in response to differing phosphorus treatments (**Tables 4**−**6**).

Stability Analysis of Juice. The precipitate weight ratio (PWR) and the serum viscosity (SV) most effectively characterize the stability of the juice. During the 2000 season, the results showed a significant difference in PWR between the HP, and RP treatments (**Table 7**). There was no significant difference between HYDRO, SENI, LP, and RP treatments. The serum viscosity values, determined by the quantity of soluble pectin in the juice did not show statistically significant changes in response to phosphorus supplementation. The PWR value was higher for juice preparations from tomatoes of HP plots (**Table 7**) during the 2000 season, and did not differ between phosphorus treatments during other seasons. The Brookfield viscosity of the juice from tomatoes of hydrophos plots was considerably higher than other treatments (**Table 7**) during 2000 season and nearly similar in all treatments during 2001 (**Table 7**) and 2002 season (**Table 8**). Serum viscosity (**Table 7**) or serum density (**Table 8**) values were also similar between all treatments during different seasons.

Phosphorus Supplementation and Lycopene Levels. The lycopene levels did not differ greatly in response to phosphorus fertilization during the different seasons. In the 2000 season, a 30% increase in lycopene level was observed in response to low phosphorus supplementation when compared to that from regular phosphorus plots (**Table 9**). There were no statistically significant differences between treatments during other seasons.

Flavor Volatiles of Tomato Juice. The analysis of the flavor volatiles of tomato juice showed the presence of acids, alcohols, aldehydes, ketones, and many other acyclic and isocyclic compounds (**Table 10**). The major peak among the volatiles was from a potentially combined elution of hexanal and hexenal at 3.535 min. Other major components included 1-penten-3-one, 6-methyl-5-hepten-2-one, and 2-octenal. Certain sulfur-containing heterocyclic compounds such as 2-isobutylthiazole

Table 4. Physicochemical Parameters of Tomato Juice Prepared from Fruits Harvested in the Year 2000[a]

	treatment				
parameters	RP	LP	HYDRO	SENI	HP
Brix (°)	6.25 ± 0.30ab	6.75 ± 0.34a	6.65 ± 0.50b	6.00 ± 0.59b	6.00 ± 0.49b
acidity (%)	0.42 ± 0.03a	0.46 ± 0.03a	0.45 ± 0.05a	0.45 ± 0.02a	0.45 ± 0.02a
pH	4.16 ± 0.03a	4.15 ± 0.04a	4.11 ± 0.08a	4.16 ± 0.03a	4.16 ± 0.08a
ash (%)	0.46 ± 0.03b	0.53 ± 0.04a	0.50 ± 0.04ab	0.50 ± 0.02ab	0.51 ± 0.04ab
TS (%)	6.10 ± 0.10b	6.61 ± 0.28cd	6.41 ± 0.09cb	5.76 ± 0.08a	6.86 ± 0.28d
Vit C (%)	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]
L	36.26 ± 0.16b	34.50 ± 0.06b	34.46 ± 0.13b	34.45 ± 0.18b	36.38 ± 0.20a
a^+	24.80 ± 0.03ba	25.12 ± 0.74ba	24.96 ± 0.46ba	25.57 ± 0.04a	24.63 ± 0.62b
b^+	15.93 ± 0.31a	14.29 ± 0.48b	14.26 ± 0.27a	14.62 ± 0.51b	15.76 ± 0.52b
a^+/b^+	1.56	1.76	1.75	1.75	1.56

[a] Statistically significant ($p < 0.05$) values are designated by different letters. [b] ND, not determined.

Table 5. Physicochemical Parameters of Tomato Juice Prepared from Fruits Harvested during the 2001 Season[a]

	treatment					
parameters	NP	RP	LP	HYDRO	SENI	COMB
Brix (°)	7.50 ± 0.60a	7.75 ± 0.34a	7.85 ± 0.57a	7.85 ± 0.60a	8.1 ± 0.81a	7.75 ± 0.62a
acidity (%)	0.49 ± 0.02a	0.54 ± 0.03a	0.54 ± 0.05a	0.52 ± 0.06a	0.54 ± 0.06a	0.51 ± 0.01a
pH	4.18 ± 0.09a	4.14 ± 0.04a	4.26 ± 0.12a	4.14 ± 0.10a	4.21 ± 0.08a	4.26 ± 0.01a
ash (%)	0.49 ± 0.15a	0.46 ± 0.15a	0.48 ± 0.15a	0.65 ± 0.09a	0.43 ± 0.10a	0.40 ± 0.13a
TS (%)	6.52 ± 0.15a	6.88 ± 0.15a	7.00 ± 0.15a	7.31 ± 0.09a	7.01 ± 0.10a	6.71 ± 0.13a
Vit C (mg·kg^{-1})	176 ± 13ba	165 ± 6b	163 ± 13b	180 ± 20a	172 ± 8ba	186 ± 11a
L	33.99 ± 0.90b	35.73 ± 0.82a	34.04 ± 1.21b	35.10 ± 0.41a	35.14 ± 0.51a	35.23 ± 0.48a
a^+	34.62 ± 0.73a	32.53 ± 1.58b	34.64 ± 1.28a	32.62 ± 1.01b	31.26 ± 1.20b	32.53 ± 1.03b
b^+	25.04 ± 0.79a	22.39 ± 1.73b	24.85 ± 1.29a	22.62 ± 1.12b	22.40 ± 0.62b	22.53 ± 1.03b
a^+/b^+	1.38	1.45	1.34	1.44	1.40	1.44

[a] Statistically significant ($p < 0.05$) values are designated by different letters.

Table 6. Physicochemical Parameters of Tomato Juice Prepared from Fruits Harvested during the 2002 Season[a]

	treatment					
parameters	NP	RP	LP	HYDRO	SENI	HP
Brix (°)	5.35 ± 0.19a	5.40 ± 0.38a	5.10 ± 0.62a	5.40 ± 0.36a	5.23 ± 0.39a	5.08 ± 0.45a
acidity (%)	0.37 ± 0.03a	0.37 ± 0.02a	0.38 ± 0.04a	0.38 ± 0.02a	0.39 ± 0.02a	0.39 ± 0.03a
ash (%)	1.05 ± 0.23ab	0.95 ± 0.18b	1.24 ± 0.27a	1.11 ± 0.15ab	1.02 ± 0.16ab	1.24 ± 0.24a
TS (%)	5.77 ± 0.23a	5.94 ± 0.51a	5.68 ± 0.42a	5.96 ± 0.50a	5.73 ± 0.38a	5.75 ± 0.69a
Vit C ($mg \cdot Kg^{-1}$)	193.1 ± 47.5a	180.4 ± 25.9a	199.6 ± 11.1a	180.0 ± 7.9a	184.5 ± 49.7a	198.4 ± 38.5a
L	33.62 ± 6.93a	33.36 ± 6.91a	31.26 ± 3.56a	30.91 ± 1.60a	29.94 ± 0.19a	30.72 ± 0.65a
a^+	27.86 ± 2.00a	26.31 ± 1.21ba	27.21 ± 2.93ba	27.99 ± 1.87a	25.43 ± 1.20b	26.79 ± 1.79ba
b^+	17.12 ± 4.85a	17.45 ± 6.59a	16.30 ± 4.37a	15.58 ± 2.00a	14.07 ± 0.64a	15.23 ± 0.60a
a^+/b^+	1.69	1.62	1.72	1.81	1.81	1.76

[a] Statistically significant ($p < 0.05$) values are designated by different letters.

Table 7. Sedimentation Stability of Tomato Juice Prepared from Fruits Harvested during the 2000 and 2001 Seasons[a]

	parameters (2000 season)		
treatment	precipitate weight ratio (%)	Brookefield viscosity (mPa.s)	serum viscosity (mPa.s)
NP	ND[b]	ND[b]	ND[b]
RP	19.19 ± 0.55b	1100 ± 115c	1.19 a
LP	18.95 ± 0.63b	1050 ± 173c	1.21 a
HP	21.12 ± 1.14a	1425 ± 96b	1.23 a
HYDRO	20.95 ± 0.27a	2225 ± 206a	1.20 a
SENI	20.07 ± 0.96ba	1150 ± 100c	1.16 b

	parameters (2001 season)		
treatment	precipitate weight ratio (%)	Brookefield viscosity (mPa.s)	serum viscosity (mPa.s)
NP	19.77 ± 0.65a	1750 ± 264.58a	1.31 bc
RP	20.52 ± 1.47a	1850 ± 310.91a	1.37 a
LP	20.23 ± 0.76a	1725 ± 287.23a	1.30 c
HP	ND[b]	ND[b]	ND[b]
HYDRO	20.49 ± 0.84a	2125 ± 585.20a	1.34 ba
SENI	19.56 ± 0.97a	1875 ± 550.00a	1.32 bc
COMB	19.71 ± 0.87a	1680 ± 278.57a	1.33 bc

[a] Statistically significant ($p < 0.05$) values are designated by different letters. [b] ND, not determined.

Table 8. Sedimentation Stability of Tomato Juice Prepared from Fruits Harvested during the 2002 Season[a]

	parameters		
treatment	precipitate weight ratio (%)	Brookefield viscosity (mPa.s)	serum density (mPa.s)
NP	21.69 ± 2.08a	6600 ± 712a	1.05a
RP	22.31 ± 2.63a	6400 ± 1030a	1.05a
LP	21.89 ± 2.30a	7075 ± 1300a	1.04a
HP	23.11 ± 2.69a	7475 ± 1866a	1.05a
HYDRO	21.49 ± 2.68a	6500 ± 739a	1.04a
SENI	21.89 ± 3.79a	7475 ± 900a	1.04a

[a] Statistically significant ($p < 0.05$) values are designated by different letters.

and benzothiazole were also detected. The peak areas of volatile components were compared for obtaining relative differences that may result from treatment and seasonal variations. Pentene-3-one, hexanal/hexenal, 6-methyl-5-hepten-2-one, 2-isobutylthiazole, and 2-octenal were the major volatile components in the juice headspace. No major differences were observed in the volatile levels in response to various phosphorus supplementation (**Table 11**). There were yearly variations in the levels of hexanal/hexenal. Very high levels of hexanal/hexenal were observed in tomato juice preparations during 2001 (**Table 11**).

Table 9. Effect of Phosphorus Supplementation on Lycopene Content of Tomato Juice[a]

	lycopene, mg/100 g tissue		
treatment	2000	2001	2002
NP	ND[b]	18.00 ± 0.82b	18.17 ± 3.24a
RP	6.13 ± 2.66b	19.73 ± 2.06ba	17.98 ± 1.53a
LP	7.69 ± 2.98a	22.06 ± 0.64a	17.32 ± 3.03a
HP	6.06 ± 2.39b	ND[b]	16.11 ± 2.78a
HYDRO	6.88 ± 3.26ba	20.89 ± 2.78a	18.42 ± 1.84a
SENI	6.91 ± 2.94ba	21.22 ± 2.12a	16.70 ± 2.42a
COMB	ND[b]	20.5 ± 0.99a	ND[b]

[a] Statistically significant ($p < 0.05$) values are designated by different letters. [b] ND, not determined.

Table 10. Headspace Volatile Components of Tomato Juice

peak no.	retention time (min)	elucidated structure
1	1.605	acetic acid
2	1.617	5-methyl, 2-hexanone
3	2.003	2-methyl furan
4	2.399	1-penten-3-one
5	2.495	3-methyl, 1- butanal
6	2.849	2-methyl, 1-butanol
7	3.035	(E)-pentenal
8	3.126	1-pentanol
9	3.136	2-ethyl-1-butanol
10	3.535	hexanal/hexenal
11	5.806	1-decanol
12	6.200	6-methyl-5-hepten-2-one
13	6.318	3-decen-2-ol
14	7.040	2-isobutylthiazole
15	7.399	2-octenal (*E*)
16	10.098	benzothiazole
17	11.870	unidentified
18	12.915	linalool
19	12.930	6,10-dimethyl-5,9-undecadien-2-one
20	15.358	decanoic acid, octadecyl ester

DISCUSSION

Often, soils appear to contain adequate amounts of phosphorus, and because of this, phosphorus fertilization requirements are not very well defined. It is generally believed that phosphorus is required primarily for root growth, and in fertilization regimes, phosphorus is not applied at later points in growth of any food crops. For tree fruit crops, phosphorus fertilization is generally not recommended. Because of intensive agricultural practices, the level of available soil phosphorus can become limiting. Under these circumstances, phosphorus supplementation would benefit the growth of crops and produce. Again, the weather patterns may play a significant role in the absorption of phosphorus from the soil if the crops are not

Table 11. Headspace Volatile Content of Tomato Juice Prepared from Fruits Harvested during Different Seasons[a]

	peak area × 10^{-4} per 10 g juice				
treatment	1-penten-3-one	hexanal/ hexenal	6-methyl-5-hepten-2-one	2-isobutylthiazole	2-octenal, (*E*)
			2000		
NP	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]
RP	30 ± 7a	71 ± 52ba	86 ± 27b	8 ± 6ba	18 ± 13ba
LP	36 ± 12a	101 ± 57a	105 ± 27ba	9 ± 2ba	19 ± 10ba
HP	36 ± 30a	98 ± 61ba	125 ± 56a	12 ± 3a	24 ± 13a
HYDRO	34 ± 11a	52 ± 32ba	90 ± 24b	8 ± 2ba	11 ± 6b
SENI	32 ± 10a	72 ± 59b	92 ± 27b	7 ± 3b	15 ± 12ba
			2001		
NP	110 ± 28a	2578 ± 95a	118 ± 44a	36 ± 19a	34 ± 11a
RP	108 ± 26a	2437 ± 40a	110 ± 12a	27 ± 12a	39 ± 10a
LP	117 ± 9a	2426 ± 60a	97 ± 11a	35 ± 8a	44 ± 30a
HP	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]
HYDRO	108 ± 16a	2482 ± 91a	100 ± 12a	26 ± 8a	51 ± 13a
SENI	116 ± 14a	2422 ± 38a	100 ± 3a	36 ± 2a	48 ± 10a
COMB	100 ± 16a	2543 ± 66a	96 ± 12a	34 ± 5a	51 ± 10a
			2002		
NP	152 ± 28a	277 ± 66ba	790 ± 339a	63 ± 15a	167 ± 83a
RP	165 ± 79a	216 ± 90ba	948 ± 339a	82 ± 26a	120 ± 57ba
LP	123 ± 56a	247 ± 120ba	795 ± 213a	87 ± 28a	131 ± 26ba
HP	112 ± 47a	130 ± 55b	503 ± 267a	71 ± 17a	67 ± 33b
HYDRO	121 ± 50a	335 ± 138a	939 ± 564a	110 ± 47a	151 ± 92ba
SENI	146 ± 27a	167 ± 84b	690 ± 210a	61 ± 13a	112 ± 52ba

[a] Statistically significant ($p < 0.05$) values are designated by different letters. [b] ND, not determined.

irrigated. During the early season, when the rainfall is abundant, the plants will be able to take up adequate amounts of phosphorus from the soil. Under conditions when the water supply is lacking, the absorption of phosphorus may become limiting, affecting plant growth, the produce quality, and the yield. In recent years, there is a renewed interest on the effects of phosphorus especially on the quality of produce. In addition to regular fertilizers such as superphosphate and N:P:K mixes, several types of foliar phosphorus formulations such as hydrophos and seniphos are in the market, and their applications have resulted in improvements in produce quality (Phosyn PLC, UK). The present study was aimed at evaluating any possible beneficial effects that phosphorus fertilizer supplementation may provide for the improvement in nutritional qualities of tomatoes.

Tomato is a major vegetable crop in North America. In southern Ontario alone, nearly a half million metric tons of processing tomatoes are produced. A major concern of tomato processing industries is the development of ideal qualities for the tomatoes, which can vary from season to season, especially in Northern latitudes. The development of high solids and adequate red color are highly desirable for the processing industry. Phosphorus fertilization is recommended for tomato by the Ontario Ministry of Agriculture Food (OMAF), and ranges from 30 to 180 kg of phosphate ($P_2 0_5$)/hectare, based on available soil phosphorus levels. Any additional benefits that may result from phosphorus supplementation on tomato quality and yield have not been studied.

In these experiments, phosphorus was supplemented through the soil as superphosphate (0:20:0) or as a phosphorus formulation spray in the form of hydrophos and seniphos. Soil supplementation of phosphorus at a high level appeared to enhance the vegetative growth of the plants at early stages. Soil phosphorus supplementation above a critical level may also tie up essential cations such as calcium, magnesium etc., thus causing deficiencies. In our experiments, we did not notice any deficiency symptoms at the high levels of phosphorus fertilization provided through the soil during the three seasons of study. The seasonal variations provided another platform to compare the effects of phosphorus supplementation. The 2000 season was very wet, the 2001 season was very dry, and the 2002 season was near ideal for growth of tomatoes.

Despite the variations in the weather and its potential influence on the metabolism of phosphorus, it was generally noticed that there were no major differences in the quality parameters of tomato juice prepared from fruits that were harvested from plots subjected to different phosphorus fertilization regimes. Neither various phosphorus treatments nor the seasons significantly influenced the quality of tomato juice. Certain parameters such as lycopene levels and viscosity values were enhanced in response to phosphorus treatments; however, such increases were not consistently observed during all the seasons. The quality parameters such as °Brix, acidity, pH, ash content, and total solids are comparable to those values reported in the literature for tomato products (*25*, *26*). These results suggest that phosphorus supplementation may not significantly influence the levels of sugars and organic acids in tomato fruits.

In tomato and tomato products, color serves as a measure of total quality due to the presence of carotenoids, predominantly lycopene and β-carotene. The major carotenoids of tomato and tomato products include lycopene, lycopene-5-6-diol, α-carotene, β-carotene, γ-carotene, δ-carotene, lutein, xanthophylls (carotenol), neurosporene, phytoene, and phytofluene. Lycopene is the major carotenoid of tomato and comprises about 83% of the total pigments (*26*). Therefore, the levels of lycopene are very important in determining the quality of processed tomato products. Not only does it determine the red color of tomato products, but also, provides antioxidant and health-regulatory properties to tomato products (*27*, *28*). The present study showed an enhancement of lycopene levels in response to phosphorus supplementation during the 2000 season; however, this effect was not reproducible during other seasons.

The characteristic sweet−sour taste and the flavor intensity of tomato and tomato products are affected by almost all of the tomato constituents (*26*, *29*, *30*). Of the more than 400 volatiles identified in tomato fruits, the following have been reported to play important roles in fresh tomato flavor: hexanal, *trans*-2-

hexenal, *cis*-3-hexenal, *cis*-3-hexenol, *trans*-2-*trans*-4-decadienal, 2-isobutylthiazole, 6-methyl-5-hepten-2-one (MHO), 1-penten-3-one, and β-ionone. Several of these compounds were identified during the analysis. Hexanal/hexenal appeared to be the major components in all treatments except during the 2002 season, when 6-methyl-5-heptene-2-one appeared to be the major component. Interestingly, headspace hexanal/hexenal levels were nearly 20-fold higher in juice preparation during the 2001 season. The reason for such drastic increase is not clear, but may have resulted from adaptations to drought conditions and decreased lipid metabolism that may have increased the availability of substrates. Hexanal/hexenal are products of the degradation of tomato acyl lipids, nearly 50% of which occurs in the phospholipids, phosphatidylcholine and phosphatidylethanolamine (*29*). The flavor compound 2-isobutylthiazole is considered important in the determination of the character of aroma and its threshold is relatively low (3.5 ppb) (*30*). The content of 2-isobutylthiazole was found to be low compared to other compounds. Phosphorus supplementation did not influence the content of 2-isobutylthiazole in tomato juice headspace.

The oxidative decomposition of carotenoids leads to the formation of terpenes and terpene-like compounds. The thermal breakdown of lycopene results in the formation of 6-methyl-5-hepten-2-one (*26*). Except in RP treatment, the relative amount of this compound was high in all treatments. The increase in 6-methyl-5-hepten-2-one could be the result of higher levels of lycopene degradation in the juice. In the 2001 and 2002 seasons, we could not find any significant difference in MHO levels between various phosphorus treatments. Therefore, environmental conditions may not affect the stability of lycopene in the fruits.

The levels of antioxidants in fruits and vegetables are important quality determinant factors, and cultural practices that enhance the levels of antioxidants are considered to be important. Several constituents of plants have antioxidant activity. These include vitamin C, vitamin E, flavonoids, and anthocyanins, phenolic components, carotenoids, etc. A recent study (*31*) which evaluated and compared the levels of phenolic antioxidants and ascorbic acid in marionberry, strawberry and corn, grown through conventional, organic and sustainable agricultural practices, concluded that organically grown produce possessed higher levels of antioxidants. The slow growth and smaller cell sizes in organically grown produce may tend to provide a higher concentration of these components when expressed in terms of fresh weight by contrast to produce grown in the presence of fertilizers, that tend to enhance growth and results in large cells with a proportionately voluminous tonoplast. Phosphorus fertilizer application did not appear to stimulate the content of vitamin C in tomato fruits. However, the antioxidant status of the fruits may be indirectly influenced by the expression and levels of antioxidant enzymes such as superoxide dismutase, catalase, and ascorbate peroxidase (*32*, *33*). Efficient operation of the antioxidant enzyme system can result in a better quality produce with longer shelf life as a result of the maintenance of cellular structure and thereby the integrity of tissue.

ABBREVIATIONS USED

NP, no phosphorus supplemented; RP, regular posphorus; LP, low phosphorus; HP, high phosphorus; HYDRO, hydrophos; SENI, seniphos; and COMB, combination.

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