JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

# Cultural System Affects Fruit Quality and Antioxidant Capacity in Strawberries

SHIOW Y. WANG,* WEI ZHENG,† AND GENE J. GALLETTA‡

Fruit Laboratory, Beltsville Agricultural Research Center, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland 20705

Cultural system [hill plasticulture (HC) versus matted row (MR)] and genotype interactions affected strawberry fruit quality. In general, fruit soluble solids content, total sugar, fructose, glucose, ascorbic acid, titratable acid, and citric acid contents were increased in the HC system. Fruit from HC also had higher flavonoid contents and antioxidant capacities. Strawberry fruit contains flavonols as well as other phenolic compounds such as anthocyanins and phenolic acids. Pelargonidin-based anthocyanins such as pelargonidin 3-glucoside, pelargonidin 3-rutinoside, and pelargonidin 3-glucoside-succinate were the predominant anthocyanins in strawberry fruit. The content of cyanidin-based anthocyanins, cyanidin 3-glucoside and cyanidin 3-glucoside-succinate, was much lower than that of pelargonidin-based anthocyanins in either system. Strawberry fruit from the HC system had significantly higher amounts of *p*-coumaroylglucose, dihydroflavonol, quercetin 3-glucoside, quercetin 3-glucuronide, kaempferol 3-glucoside, kaempferol 3-glucuronide, cyanidin 3-glucoside, pelargonidin 3-glucoside, pelargonidin 3-rutinoside, cyanidin 3-glucoside-succinate, and pelargonidin 3-glucoside-succinate. Fruits from plants grown in the MR system generally had the lowest contents of phenolic acids, flavonols, and anthocyanins. Strawberry fruit grown under HC conditions had significantly higher peroxyl radicals ($ROO^{\bullet}$) absorbance capacity (ORAC).

**KEYWORDS: Antioxidant; flavonoids; fruit; genotypes; strawberry**

## INTRODUCTION

Strawberry growers have found high profitability in utilizing the raised bed, or hill plasticulture, system (*1*, *2*). This system has advantages of enhanced weed control, advanced harvest, increased yield and fruit size, prevention of bed erosion, and increased fruit cleanliness (*3*−*5*). There are a wide variety of synthetic mulches that have been used in the raised bed culture system, but black polyethylene mulch has become the standard for the annual production of eastern U.S. strawberries. Himelrick (*4*) showed that plants grown with black plastic mulch produce a higher number of runners and strawberry fruit than do plants grown with clear or white plastic mulches. Total fruit weight was increased by the use of black plastic mulch compared to bare soil (*4*).

Strawberries contain high levels of antioxidant compounds, which provide protection against harmful free radicals and have been associated with lower incidence and mortality rates of cancer and heart disease in addition to a number of other health benefits (*6*−*12*). Our previous studies (*13*, *14*) have shown that strawberries (*Fragaria* × *ananassa* Duch.) have high oxygen radical absorbance activity against peroxyl radicals ($ROO^{\bullet}$), superoxide radicals ($O_2^{\bullet-}$), hydrogen peroxide ($H_2O_2$), hydroxyl radicals ($OH^{\bullet}$), and singlet oxygen ($^1O_2$), and their antioxidant activities were different among varieties (*13*, *14*). There is a positive correlation between antioxidant activity and total phenolic or anthocyanin content (*13*, *14*). However, no information is available on the effects of environmental factors such as cultural systems on the scavenging capacity of strawberry against active oxygen species. The objective of the present study was to evaluate the different cultural systems [hill plasticulture (HC) and conventional matted row (MR)] on fruit quality and antioxidant capacity against the $ROO^{\bullet}$ radical in 14 different strawberry cultivars and selections.

## MATERIALS AND METHODS

**Chemicals.** (*R*)-Phycoerythrin (R-PE) from *Porphydium cruentum* was purchased from Sigma (St. Louis, MO). 2′,2′-Azobis(2-amidinopropane) dihydrochloride (AAPH) was purchased from Wako Chemicals USA Inc. (Richmond, VA). 6-Hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox) was obtained from Aldrich (Milwaukee, WI).

**Plant Material and Field Experiments.** Fourteen strawberry cultivars and selections were grown on the North Farm of the Henry A. Wallace Agricultural Research Center at Beltsville, MD, on either flat, matted-row (MR) beds without plastic mulch (1.1 m apart in plots permitted to develop to 1.5 m long) or on hill plasticulture (HC) beds covered with black polyethylene mulch (six-plant double-hill plots planted 30 × 30 cm apart on raised beds covered with black

* Author to whom correspondence should be addressed [telephone (301) 504-5776; fax (301) 504-5062; e-mail wangs@ba.ars.usda.gov].
† Visiting scientist from the Institute of Environmental Science, Zhejiang University at Yuquan, Hangzhou, Zhejiang 310027, People's Republic of China.
‡ Deceased.

10.1021/jf020614i 
Published on Web 09/28/2002

polyethylene mulch and spaced 1.8 m apart). Each type of planting was supplied with drip tubing down the center of each row. The MR planting received 112 kg·ha$^{-1}$ nitrogen (N) from 10-10-10 during the growing season and no fertilizer in the spring. The HC planting received 34 kg·ha$^{-1}$ N (10-10-10) at planting time, 45 kg·ha$^{-1}$ N ($NH_4NO_3$) through the drip line in the summer and fall, and 17 kg·ha$^{-1}$ N ($NH_4NO_3$) through the drip line in the spring; supplemental irrigation was applied to both fields. During the fruiting season, the average maximum temperature was 15.5 °C, minimum temperature was 8.5 °C, and rainfall was 5.84 mm. The mature fruit was harvested from four plots of a replicated complete block design (RCB) for the matted-row field and four plots of the RCB for the double-hill field. Twenty ripe fruits with well-developed red color were selected around 9:00 a.m. from each cultivar in each plot and were used for chemical analyses.

**Soluble Solids, Titratable Acid, and Ascorbic Acid Determinations.** Soluble solids content (SSC) of the fruit was determined at 20 °C on a Bausch and Lomb refractometer. Titratable acid (TA) was determined by diluting each 5 mL aliquot of strawberry juice to 100 mL with distilled water and then titrating to pH 8.2 using 0.1 N NaOH. Acidity was expressed as milligrams of citric acid per 100 mL of juice. Ascorbic acid was determined on the basis of the reaction of 2,6-dichloroindophenol dye and ascorbic acid as described by Lundergan and Moore (*15*).

**Sugar and Organic Acid Analysis.** The extraction, purification, and derivatization procedures for nonstructural sugars and organic acids have been described previously (*16*). A Hewlett-Packard 5880 gas chromatograph equipped with a flame ionization detector and a fused silica capillary (dimethylsilicone fluid, 12.5 m × 0.2 mm) was used for separation of sugars and organic acids. Sugars and organic acids were quantified by comparing peak area with those of standards.

**Oxygen Radical Absorbance Capacity (ORAC) Assay.** To prepare the juice samples, three 100 g samples of berries from three replicates of each cultivar of each treatment were pulverized and then centrifuged at 14000*g* for 20 min at 4 °C. The supernatants were transferred to vials stored at −80 °C and then used for ORAC analyses.

The procedures for the ORAC assay on strawberries were modified from the previously described method of Cao et al. (*17*). This assay measures the effect of antioxidant components in fruit juices of strawberries on the decline in R-PE fluorescence induced by a peroxyl radical generator, AAPH. The reaction mixture contained 1.7 mL of 75 mM phosphate buffer (pH 7.0), 100 μL of R-PE (3.4 mg/L), 100 μL of 320 mM AAPH, and 100 μL of sample. Phosphate buffer was used as a blank, and 1 μM Trolox (a water-soluble α-tocopherol analogue) was used as a standard during each run. The final volume of 2 mL was used in a 10-mm-wide fluorometer cuvette. R-PE, phosphate buffer, and samples were preincubated at 37 °C for 15 min. The reaction was started by the addition of AAPH. Fluorescence was measured and recorded every 5 min at the emission of 570 nm and excitation of 540 mm using a Shimadzu RF-Mini 150 recording fluorometer (Columbia, MD) until the fluorescence of the last reading declined to <5% of the first reading (~70 min). One blank, one standard, and a maximum of 10 samples were analyzed at the same time. Each sample was repeated three times. The ORAC value refers to the net protection area under the quenching curve of R-PE in the presence of an antioxidant. The final results (ORAC value) were calculated and expressed using Trolox equivalents per gram on a fresh weight basis (*17*)

$$\text{ORAC value } (\mu\text{M}) = 20K(S_{\text{sample}} - S_{\text{blank}})/(S_{\text{Trolox}} - S_{\text{blank}})$$

where $K$ = sample dilution factor and $S$ = the area under the fluorescence decay curve of the sample, Trolox, or blank, which is calculated as follows:

$$S = (0.5 + f_5/f_0 + f_{10}/f_0 + f_{15}/f_0 + f_{20}/f_0 + f_{25}/f_0 + f_{30}/f_0 + \ldots + f_{60}/f_0 + f_{65}/f_0 + f_{70}/f_0) \times 5$$

$f_0$ = initial fluorescence at 0 min and $f_i$ = fluorescence measurement at time $i$.

**HPLC Analysis of Strawberry Anthocyanins and Phenolic Compounds.** High-performance liquid chromatography (HPLC) was used to separate and determine individual anthocyanins and phenolic compounds in strawberry tissue samples. Fruit samples of 5 g were extracted twice with 15 mL of acetone using a Polytron homogenizer (Brinkmann Instruments, Inc., Westbury, NY) for 1 min. Extracts (30 mL) were combined and concentrated to 1 mL using a Buchler Evapomix (Fort Lee, NJ) in a water bath at 35 °C. The concentrated sample was dissolved in 10 mL of acidified water (3% formic acid) and then passed through a $C_{18}$ Sep-Pak cartridge (Waters), which was previously activated with methanol followed by water and then 3% aqueous formic acid. Anthocyanins and other phenolics were adsorbed onto the column while sugars, acids, and other water-soluble compounds were eluted with 10 mL of 3% aqueous formic acid. The anthocyanins and other phenolics were then recovered with 2.0 mL of acidified methanol containing 3% formic acid. The methanol extract was passed through a 0.45 μm membrane filter (Millipore, MSI, Westboro, MA), and 20 μL was analyzed by HPLC. The samples were analyzed using a Waters (Waters Associates, Millipore, Milford, MA) HPLC system equipped with two pumps (600 E system controller) coupled with a photodiode array detector (Waters 990 series). Samples were injected at ambient temperature (20 °C) onto a reverse phase Nova-Pak $C_{18}$ column (150 × 3.9 mm, particle size = 4 μm) with a guard column (Nova-Pak $C_{18}$, 20 × 3.9 mm, particle size = 4 μm) (Sentry guard holder universal). The mobile phase was acidified water containing 2.5% formic acid (A) and acetonitrile (B) in a linear gradient from 5% to 20% B in the first 15 min, followed by a linear gradient from 20 to 30% B for 5 min, then an isocratic mixture for 5 min, followed by a linear gradient from 30 to 90% B for 5 min, and then an isocratic mixture for 2 min before returning to the initial conditions. The flow rate was 1.0 mL/min, and the wavelengths of detection were set at 320, 350, and 510 nm. Scanning between 240 and 550 nm was performed, and data were collected by the Waters 990 3-D chromatography data system. Retention times and spectra were compared to those of pure standards.

**Statistical Analysis.** Data were subjected to analysis of variance using NCSS (*18*), and the effect of cultural systems and genotypes on fruit quality (SSC, TA, ascorbic acid, sugars, and organic acids) and the values of flavonoid concentrations in strawberry fruit juice and their antioxidant capacity were evaluated by the Tukey-Kramer multiple-comparison test used in NCSS. Differences at $p < 0.05$ were considered significant. Correlation and regression analyses between strawberry flavonoids and their antioxidant capacity were also performed using NCSS (*18*).

## RESULTS AND DISCUSSION

**Soluble Solids Content, Titratable Acidity, and Ascorbic Acid.** Strawberry flavor is derived from the interactive taste and aroma of many chemical constituents. High sugars and relatively high acid content are required for good flavor (*19*). Although not all strawberries with high SSC will necessarily be of good quality, the absence of high SSC makes good quality unlikely. The fruit SSC and TA contents varied with genotype (**Table 1**). Galletta et al. (*20*) reported that SSC in strawberry fruit generally is in the range of 7−12% depending on genotype. Shaw (*21*) reported that genotypic SSC ranges for two sets of California strawberry seedling selections ($n$ = 13, 12) were 5.28−8.74 and 6.06−8.73%, respectively. Among the genotypes grown on HC, Earliglow and B 28 had the greatest SSC. Earliglow fruit also had the greatest SSC among the MR genotypes. The average SSC of fruit grown in HC was higher than that of fruit grown in MR (**Table 1**). The only exception was B 35, which had higher SSC values when grown in MR than when grown in HC. Redchief and US 292 had the greatest amounts of TA. The average fruit TA content was greater for genotypes grown in HC than in MR. The only exceptions were Earliglow and Redchief, which had higher TA content when grown in MR than in HC.

Strawberries are a rich source of vitamin C (ascorbic acid). High ascorbic acid content was found in fruits of Earliglow, B28, Northeaster, Lester, Redchief, and Mohawk (**Table 1**). In

**Table 1.** Effect of Cultural Systems [Hill Plasticulture (HC) and Matted Row (MR)] on Soluble Solids Content (SSC), Titratable Acids (TA), Malic Acid, Citric Acid, and Ascorbic Acid (AA) in Fruit of Various Strawberry Genotypes[a]

| genotype | cultural system | SSC (%) | TA (%) | malic acid (%) | citric acid (%) | total organic acids (%) | AA (mg/100 g of fresh wt) |
|---|---|---|---|---|---|---|---|
| Allstar | MR | 6.8 ± 0.1 | 0.42 ± 0.01 | 0.09 ± 0.02 | 0.40 ± 0.01 | 0.49 ± 0.02 | 73.4 ± 1.5 |
| | HC | 6.9 ± 0.1 | 0.72 ± 0.06 | 0.11 ± 0.03 | 0.54 ± 0.02 | 0.65 ± 0.03 | 78.3 ± 2.6 |
| Earliglow | MR | 9.1 ± 0.2 | 0.91 ± 0.04 | 0.10 ± 0.01 | 0.69 ± 0.03 | 0.79 ± 0.02 | 89.2 ± 1.9 |
| | HC | 9.7 ± 0.1 | 0.74 ± 0.05 | 0.08 ± 0.01 | 0.55 ± 0.02 | 0.63 ± 0.01 | 102.3 ± 2.3 |
| Delmarvel | MR | 7.6 ± 0.2 | 0.64 ± 0.03 | 0.19 ± 0.03 | 0.47 ± 0.02 | 0.66 ± 0.02 | 76.8 ± 1.2 |
| | HC | 8.4 ± 0.3 | 0.88 ± 0.07 | 0.06 ± 0.01 | 0.73 ± 0.03 | 0.79 ± 0.02 | 84.4 ± 2.8 |
| Latestar | MR | 7.0 ± 0.2 | 0.51 ± 0.02 | 0.06 ± 0.00 | 0.40 ± 0.01 | 0.64 ± 0.01 | 74.3 ± 1.2 |
| | HC | 7.6 ± 0.3 | 0.62 ± 0.01 | 0.08 ± 0.01 | 0.48 ± 0.02 | 0.56 ± 0.01 | 80.3 ± 2.6 |
| Lester | MR | 6.3 ± 0.3 | 0.57 ± 0.01 | 0.04 ± 0.01 | 0.47 ± 0.00 | 0.51 ± 0.01 | 86.4 ± 2.3 |
| | HC | 7.7 ± 0.4 | 0.69 ± 0.02 | 0.07 ± 0.01 | 0.55 ± 0.02 | 0.63 ± 0.02 | 96.3 ± 1.5 |
| Mohawk | MR | 7.4 ± 0.2 | 0.64 ± 0.04 | 0.05 ± 0.01 | 0.51 ± 0.01 | 0.56 ± 0.01 | 88.4 ± 1.3 |
| | HC | 8.3 ± 0.3 | 0.85 ± 0.05 | 0.12 ± 0.02 | 0.63 ± 0.02 | 0.75 ± 0.02 | 93.2 ± 3.7 |
| Northeaster | MR | 7.0 ± 0.2 | 0.70 ± 0.04 | 0.06 ± 0.01 | 0.54 ± 0.00 | 0.60 ± 0.01 | 83.3 ± 1.8 |
| | HC | 7.8 ± 0.3 | 0.86 ± 0.06 | 0.06 ± 0.01 | 0.70 ± 0.01 | 0.76 ± 0.01 | 98.8 ± 1.7 |
| Redchief | MR | 7.8 ± 0.1 | 1.07 ± 0.02 | 0.14 ± 0.01 | 0.81 ± 0.02 | 0.95 ± 0.01 | 89.0 ± 2.8 |
| | HC | 8.4 ± 0.2 | 0.92 ± 0.05 | 0.11 ± 0.00 | 0.68 ± 0.01 | 0.79 ± 0.00 | 95.6 ± 3.5 |
| B28 | MR | 7.7 ± 0.2 | 0.81 ± 0.03 | 0.16 ± 0.02 | 0.59 ± 0.01 | 0.75 ± 0.01 | 89.6 ± 2.6 |
| | HC | 9.8 ± 0.3 | 0.91 ± 0.04 | 0.17 ± 0.02 | 0.63 ± 0.02 | 0.80 ± 0.02 | 99.1 ± 2.3 |
| B35 | MR | 7.7 ± 0.1 | 0.67 ± 0.05 | 0.07 ± 0.01 | 0.54 ± 0.01 | 0.61 ± 0.01 | 73.0 ± 2.5 |
| | HC | 6.5 ± 0.2 | 0.90 ± 0.01 | 0.05 ± 0.01 | 0.73 ± 0.03 | 0.78 ± 0.02 | 78.8 ± 2.9 |
| B244-89 | MR | 7.9 ± 0.2 | 0.87 ± 0.03 | 0.33 ± 0.07 | 0.40 ± 0.02 | 0.73 ± 0.03 | 84.4 ± 2.0 |
| | HC | 8.5 ± 0.1 | 0.89 ± 0.02 | 0.36 ± 0.08 | 0.44 ± 0.01 | 0.80 ± 0.04 | 94.1 ± 1.9 |
| MEUS 8 | MR | 7.5 ± 0.1 | 0.73 ± 0.01 | 0.12 ± 0.03 | 0.64 ± 0.05 | 0.76 ± 0.04 | 75.3 ± 2.1 |
| | HC | 8.8 ± 0.2 | 0.83 ± 0.02 | 0.06 ± 0.01 | 0.76 ± 0.04 | 0.82 ± 0.02 | 81.9 ± 1.9 |
| MEUS 9 | MR | 7.9 ± 0.1 | 0.85 ± 0.03 | 0.08 ± 0.00 | 0.56 ± 0.04 | 0.64 ± 0.02 | 70.6 ± 1.7 |
| | HC | 8.6 ± 0.3 | 0.74 ± 0.02 | 0.09 ± 0.01 | 0.69 ± 0.03 | 0.78 ± 0.02 | 84.1 ± 1.5 |
| US 292 | MR | 6.0 ± 0.1 | 0.94 ± 0.04 | 0.35 ± 0.02 | 0.46 ± 0.02 | 0.81 ± 0.02 | 79.2 ± 1.8 |
| | HC | 6.9 ± 0.1 | 0.98 ± 0.05 | 0.41 ± 0.02 | 0.54 ± 0.03 | 0.95 ± 0.03 | 86.1 ± 1.3 |
| mean | MR | 7.4 ± 0.2 | 0.70 ± 0.03 | 0.13 ± 0.01 | 0.53 ± 0.03 | 0.67 ± 0.02 | 80.9 ± 2.2 |
| | HC | 8.1 ± 0.3 | 0.82 ± 0.04 | 0.13 ± 0.01 | 0.61 ± 0.04 | 0.74 ± 0.03 | 89.5 ± 2.8 |
| significance[b] | | | | | | | |
| genotype (G) | | * | ns | * | * | * | * |
| cultural system (C) | | * | ns | * | * | * | * |
| G × C | | * | ns | * | * | * | * |

[a] Data expressed as mean ± SEM. [b] *, ns, significant or nonsignificant, respectively, at $p \leq 0.05$.

general, vitamin C concentrations were higher than flavonoid concentrations and had powerful antioxidant properties. Ascorbic acid content was correlated with antioxidant activities (ORAC) in strawberries ($r = 0.940$). Ascorbic acid also indirectly contributes to several key oxidative and reductive enzyme systems and has the ability to regenerate other biologically important antioxidants, such as glutathione and vitamin E, into their reduced state (*22*, *23*). The biological function of vitamin C is based on its ability to donate electrons, which provides intra- and extracellular reducing power for a variety of biochemical reactions. It has been reported that the reducing power of vitamin C is capable of neutralization of most of the physiologically relevant reactive oxygen and nitrogen species in the human body (*24*). The substantially high cellular levels of vitamin C provide antioxidant protection to the eye against photosynthetically generated free radicals (*25*) and against plasma and low-density lipoprotein oxidation (*26*, *27*). Vitamin C also functions as a reducing agent for mixed-function oxidases involved in drug metabolism by inactivating a wide variety of xenobiotic substances and hormones (*28*). Furthermore, like vitamin E, it plays an important role in reducing oxygen toxicity and is also an excellent nitrite-trapping agent for preventing gastric cancer (*29*).

**Sugars.** Fructose, glucose, and sucrose were found to be the three major sugars, comprising >65% of the total SSC in fruit of strawberry cultivars and selections (**Table 2**). The amounts of these sugars in the fruit were quite different among genotypes. In general, fruit contained lower sucrose concentrations compared to fructose and glucose. The low sucrose content in the fruit is probably due to enzymatic hydrolysis after translocation from the leaves (*30*). The proportions of fructose, glucose, and sucrose are important in the perception of fruit quality because fructose is 1.8 times sweeter than sucrose (*31*), whereas the sweetness of glucose is only 60% that of sucrose (*32*, *33*). When the plants were grown in MR, fruit from Delmarvel, B 28, Mohawk, Northeaster, B244-89, MEUS 8, and MEUS 9 had higher fructose contents than fruit of other cultivars. Northeaster, Mohawk, B244-89, and MEUS 9 grown in MR were found to have higher glucose contents than fruit of other cultivars. Among the genotypes grown in MR, Earliglow and Delmarvel had the highest sucrose contents and B 28 had the lowest. The highest fruit glucose contents among the genotypes grown in HC were found in MEUS 9, Northeaster, B 28, and MEUS 8, whereas US 292 contained the least. B 28, MEUS 9, Lester, Mohawk, Northeaster, and MEUS 8 grown in HC had the highest content of fructose, whereas US 292 had the lowest. The sucrose contents of fruit from the HC system were highest in Delmarvel, Mohawk, and Allstar and lowest in B 28.

A comparison between fruit sugar content of strawberry fruit produced in HC versus MR revealed that fruit of strawberry plants grown in HC had higher total sugar contents compared to those grown in MR. Fruits of all genotypes grown in HC had higher fructose contents than those grown in MR except for US 292. The fruit glucose contents of all genotypes grown in HC were higher than those grown in MR except in B244-89. Fruits of all genotypes grown in MR had higher concentrations of sucrose except for Delmarvel, Latestar, Lester, Mohawk, and Northeaster. In general, strawberry fruits from plants grown

**Table 2.** Effect of Cultural Systems [Hill Plasticulture (HC) and Matted Row (MR)] on Sugar Content in Fruit of Various Strawberry Genotypes[a]

| genotype | cultural system | sugar (%) | | | |
|---|---|---|---|---|---|
| | | fructose | glucose | sucrose | total |
| Allstar | MR | 1.76 ± 0.11 | 1.63 ± 0.05 | 1.49 ± 0.07 | 4.88 ± 0.06 |
| | HC | 2.10 ± 0.09 | 1.82 ± 0.04 | 1.19 ± 0.10 | 5.11 ± 0.07 |
| Earliglow | MR | 1.86 ± 0.08 | 1.78 ± 0.04 | 1.84 ± 0.08 | 5.48 ± 0.08 |
| | HC | 2.26 ± 0.10 | 2.42 ± 0.09 | 0.96 ± 0.04 | 5.64 ± 0.07 |
| Delmarvel | MR | 2.46 ± 0.06 | 1.69 ± 0.05 | 1.79 ± 0.09 | 5.94 ± 0.06 |
| | HC | 2.63 ± 0.08 | 2.16 ± 0.08 | 2.14 ± 0.14 | 6.93 ± 0.09 |
| Latestar | MR | 1.99 ± 0.08 | 1.76 ± 0.04 | 0.33 ± 0.05 | 4.08 ± 0.03 |
| | HC | 2.08 ± 0.14 | 2.43 ± 0.08 | 0.60 ± 0.08 | 5.11 ± 0.10 |
| Lester | MR | 2.15 ± 0.10 | 1.84 ± 0.14 | 0.61 ± 0.04 | 4.60 ± 0.08 |
| | HC | 2.55 ± 0.17 | 2.21 ± 0.15 | 0.99 ± 0.05 | 5.75 ± 0.11 |
| Mohawk | MR | 2.38 ± 0.11 | 2.24 ± 0.05 | 0.78 ± 0.08 | 5.40 ± 0.07 |
| | HC | 2.54 ± 0.00 | 2.48 ± 0.10 | 1.12 ± 0.09 | 6.14 ± 0.05 |
| Northeaster | MR | 2.38 ± 0.05 | 2.40 ± 0.08 | 0.33 ± 0.02 | 5.11 ± 0.04 |
| | HC | 2.54 ± 0.00 | 2.63 ± 0.06 | 0.60 ± 0.07 | 5.77 ± 0.04 |
| Redchief | MR | 2.02 ± 0.02 | 1.47 ± 0.04 | 0.83 ± 0.05 | 4.32 ± 0.03 |
| | HC | 2.21 ± 0.07 | 1.88 ± 0.06 | 0.74 ± 0.04 | 4.83 ± 0.05 |
| B28 | MR | 2.36 ± 0.09 | 1.95 ± 0.05 | 0.07 ± 0.01 | 4.38 ± 0.05 |
| | HC | 3.05 ± 0.12 | 2.60 ± 0.11 | 0.10 ± 0.01 | 5.75 ± 0.08 |
| B35 | MR | 1.89 ± 0.07 | 1.64 ± 0.05 | 0.59 ± 0.03 | 4.12 ± 0.05 |
| | HC | 2.21 ± 0.07 | 1.71 ± 0.04 | 0.38 ± 0.05 | 4.30 ± 0.06 |
| B244-89 | MR | 2.30 ± 0.03 | 2.08 ± 0.02 | 0.37 ± 0.00 | 4.75 ± 0.02 |
| | HC | 2.39 ± 0.04 | 2.00 ± 0.01 | 0.38 ± 0.01 | 4.77 ± 0.02 |
| MEUS 8 | MR | 2.23 ± 0.06 | 1.89 ± 0.09 | 0.23 ± 0.02 | 4.35 ± 0.04 |
| | HC | 2.46 ± 0.05 | 2.50 ± 0.13 | 0.18 ± 0.01 | 5.14 ± 0.06 |
| MEUS 9 | MR | 2.21 ± 0.07 | 2.08 ± 0.06 | 0.25 ± 0.02 | 4.54 ± 0.03 |
| | HC | 2.70 ± 0.12 | 2.72 ± 0.16 | 0.13 ± 0.01 | 5.55 ± 0.10 |
| US 292 | MR | 1.79 ± 0.03 | 1.22 ± 0.02 | 0.76 ± 0.00 | 3.77 ± 0.02 |
| | HC | 1.73 ± 0.02 | 1.52 ± 0.12 | 0.75 ± 0.01 | 4.01 ± 0.05 |
| mean | MR | 2.13 ± 0.02 | 1.83 ± 0.03 | 0.73 ± 0.05 | 4.69 ± 0.04 |
| | HC | 2.39 ± 0.04 | 2.22 ± 0.14 | 0.73 ± 0.04 | 5.34 ± 0.06 |
| significance[b] | | | | | |
| genotype (G) | | * | * | * | * |
| cultural system (C) | | * | * | ns | * |
| G × C | | * | * | ns | * |

[a] Data expressed as mean ± SEM. [b] **, ns, significant or nonsignificant, respectively, at $p \leq 0.05$.

in the HC system yielded higher levels of total sugar, fructose, and glucose contents than those grown in MR (**Table 2**).

**Organic Acids.** Organic acids are minor components of strawberry fruit, but they are important attributes of flavor that, in combination with sugars, have an impact on the sensory quality of strawberry fruit. There were distinct differences in organic acid content among the genotypes examined. The total organic acid level was positively correlated with titratable acitity ($r = 0.96$). Citric acid was the major organic acid found in the strawberries (**Table 1**). Earliglow, Delmarvel, Redchief, B-35, and MEUS 8 had greater amounts of malic acid when grown in MR compared to those grown in HC. The genotype with the highest fruit citric acid content was MEUS 8 among those grown in HC and Redchief among those grown in MR. Fruit of B244-89 had the lowest citric acid content among all of the genotypes grown in both HC and MR. The fruit citric acid content of Earliglow and Redchief was higher when they were grown in MR compared to when they were grown in HC. Strawberries from plants grown in HC had a higher average of citric and malic acid compared to those grown in MR (**Table 1**).

**Quantitation of Phenolic Compounds in Strawberries and Antioxidant Activity of Phenolics.** Flavonoids are a group of polyphenolic compounds ubiquitously found in fruits and vegetables. The increasing interest in flavonoids is due to the appreciation of their broad pharmacological activity. Beneficial effects of flavonoids have been described for diabetes mellitus, allergies, cancer, viral infections, headache, stomach and duodenal ulcers, parodentosis, and inflammatory diseases (*34*). Different flavonoids have different antioxidant capacities. The antioxidant potential of flavonoids is dependent on the number and arrangement of hydroxyl groups across the structure, as well as the presence of electron-donating and electron-withdrawing substituents in the ring structure (*35*). The hydroxyl radical scavenging activities of flavonoids increase with the number of hydroxyl groups substituted on the B-ring, especially at position 3′ (*28*, *35*). A single hydroxy substituent generates little antioxidant activity. Genotypes and cultural practices affect flavonoid content in strawberry (**Table 2**). A great variation in the flavonoid content of different fruit crops and with different growing conditions has also been reported (*14*, *36*, *37*).

The HPLC analysis of strawberry fruit juice including ellagic acid, ellagic acid glucoside, *p*-coumaroylglucose, quercetin 3-glucoside, quercetin 3-glucuronide, kaempferol 3-glucoside, and kaempferol 3-glucuronide is presented in **Table 3**. Ellagic acid content in strawberry juice ranged from 4.1 to 13.3 $\mu$g/g of fresh wt. Ellagic acid is a naturally occurring phenolic constituent of many plant species (*38*) and has shown promising antimutagenic and anticarcinogenic activities against chemical-induced cancers (*39*, *40*). In nature, ellagic acid may occur in free form, but it is more commonly present as esters of the diphenic acid analogue on glucose. These ellagitannins differ in solubility, mobility, and reactivity in plant as in animal systems (*39*, *40*). Ellagic acid in pure form is poorly absorbed through the bowel and is mostly biologically unavailable, but ellagitannins are very available to absorption in mammalian systems (*40*). Strawberries contained both ellagic acid and ellagic acid glucoside, and large differences in levels have been found among species, cultivars, tissues, and environmental

**Table 3.** Effect of Cultural Systems [Hill Plasticulture (HC) and Matted Row (MR)] on *p*-Coumaroylglucose, Dihydroflavonol, Quercetin 3-Glucoside and Quercetin 3-Glucuronide, Kaempferol 3-Glucoside, and Kaempferol 3-Glucuronide Contents (Micrograms per Gram of Fresh Weight) in Fruit Juice of Various Strawberry Genotypes[a]

| genotype | cultural system | ellagic acid | ellagic acid glucoside[b] | *p*-coumaroyl-glucose[c] | quercetin 3-glucoside and quercetin 3-glucuronide[d] | kaempferol 3-glucoside[d] | kaempferol 3-glucuronide[d] |
|---|---|---|---|---|---|---|---|
| Allstar | MR | 7.6 ± 0.3 | 18.1 ± 0.4 | 21.9 ± 1.2 | 8.1 ± 0.5 | 2.21 ± 0.2 | 1.08 ± 0.3 |
| | HC | 8.8 ± 0.4 | 20.5 ± 0.5 | 28.5 ± 1.5 | 11.6 ± 0.8 | 1.97 ± 0.1 | 2.62 ± 0.4 |
| Earliglow | MR | 9.2 ± 0.2 | 21.3 ± 0.7 | 25.7 ± 2.1 | 21.2 ± 1.2 | 2.19 ± 0.1 | 2.07 ± 0.1 |
| | HC | 10.2 ± 0.3 | 26.3 ± 0.8 | 43.3 ± 3.9 | 35.1 ± 3.4 | 3.32 ± 0.2 | 2.71 ± 0.2 |
| Delmarvel | MR | 5.6 ± 0.1 | 12.8 ± 0.2 | 19.4 ± 2.1 | 4.3 ± 1.5 | 1.68 ± 0.1 | 2.03 ± 0.0 |
| | HC | 5.5 ± 0.1 | 13.9 ± 0.3 | 44.0 ± 5.9 | 15.7 ± 2.8 | 1.91 ± 0.1 | 1.80 ± 0.1 |
| Latestar | MR | 9.6 ± 0.6 | 13.7 ± 0.7 | 17.7 ± 1.7 | 21.3 ± 1.3 | 2.63 ± 0.2 | 1.98 ± 0.2 |
| | HC | 12.7 ± 0.7 | 17.2 ± 0.8 | 28.5 ± 2.5 | 30.5 ± 2.2 | 4.58 ± 0.4 | 1.42 ± 0.1 |
| Lester | MR | 9.7 ± 0.5 | 14.7 ± 0.5 | 21.0 ± 1.8 | 22.4 ± 1.0 | 4.59 ± 1.5 | 1.91 ± 0.1 |
| | HC | 12.5 ± 0.6 | 18.6 ± 0.9 | 29.2 ± 2.1 | 27.1 ± 1.1 | 5.40 ± 0.2 | 2.52 ± 0.2 |
| Mohawk | MR | 8.9 ± 0.2 | 25.6 ± 1.8 | 21.7 ± 2.2 | 12.7 ± 1.4 | 1.88 ± 0.4 | 6.16 ± 1.0 |
| | HC | 10.2 ± 0.3 | 33.9 ± 2.0 | 31.4 ± 2.4 | 18.9 ± 1.5 | 4.00 ± 0.5 | 2.16 ± 0.9 |
| Northeaster | MR | 9.1 ± 0.1 | 14.9 ± 0.3 | 33.0 ± 1.8 | 25.7 ± 1.4 | 3.86 ± 0.1 | 1.74 ± 0.2 |
| | HC | 9.8 ± 0.2 | 16.4 ± 0.4 | 41.6 ± 2.1 | 32.0 ± 1.6 | 4.56 ± 0.1 | 0.77 ± 0.1 |
| Redchief | MR | 11.9 ± 0.2 | 13.8 ± 0.1 | 16.9 ± 0.7 | 35.1 ± 1.2 | 3.96 ± 0.1 | 3.13 ± 0.2 |
| | HC | 12.1 ± 0.2 | 13.7 ± 0.2 | 20.8 ± 0.9 | 40.3 ± 1.3 | 3.94 ± 0.1 | 2.22 ± 0.2 |
| B28 | MR | 4.1 ± 0.3 | 12.4 ± 4.7 | 17.7 ± 2.5 | 13.3 ± 2.3 | 2.56 ± 0.2 | 1.81 ± 0.6 |
| | HC | 6.7 ± 0.5 | 39.3 ± 5.6 | 30.7 ± 3.2 | 27.2 ± 3.2 | 4.16 ± 0.3 | 4.77 ± 0.7 |
| B35 | MR | 5.3 ± 0.3 | 12.8 ± 0.2 | 26.8 ± 2.1 | 9.1 ± 1.2 | 5.04 ± 0.1 | 3.22 ± 0.1 |
| | HC | 6.8 ± 0.4 | 12.0 ± 0.1 | 29.2 ± 2.3 | 14.4 ± 1.3 | 5.42 ± 0.2 | 2.96 ± 0.1 |
| B244-89 | MR | 8.3 ± 0.3 | 9.7 ± 0.9 | 17.8 ± 0.2 | 13.5 ± 1.5 | 3.54 ± 0.4 | 0.90 ± 0.1 |
| | HC | 13.3 ± 0.5 | 13.7 ± 0.8 | 19.2 ± 0.3 | 21.3 ± 1.9 | 1.64 ± 0.3 | 0.45 ± 0.1 |
| MEUS 8 | MR | 10.6 ± 0.4 | 24.1 ± 1.8 | 4.2 ± 0.1 | 10.0 ± 1.5 | 1.02 ± 0.1 | 1.53 ± 0.1 |
| | HC | 12.5 ± 0.5 | 32.8 ± 2.1 | 4.0 ± 0.1 | 16.7 ± 1.6 | 1.39 ± 0.1 | 1.19 ± 0.1 |
| MEUS 9 | MR | 7.0 ± 0.2 | 15.0 ± 1.2 | 1.9 ± 0.1 | 11.0 ± 0.2 | 0.83 ± 0.0 | 0.95 ± 0.1 |
| | HC | 6.9 ± 0.1 | 21.0 ± 1.4 | 2.6 ± 0.2 | 10.8 ± 0.1 | 0.94 ± 0.1 | 1.46 ± 0.2 |
| US 292 | MR | 5.9 ± 0.2 | 13.4 ± 0.9 | 16.7 ± 1.5 | 23.1 ± 1.5 | 7.75 ± 0.1 | 0.54 ± 0.1 |
| | HC | 6.3 ± 0.1 | 18.3 ± 1.2 | 23.5 ± 1.6 | 31.4 ± 2.0 | 7.86 ± 0.2 | 0.39 ± 0.0 |
| mean | MR | 8.1 ± 0.2 | 9.6 ± 0.9 | 10.9 ± 1.1 | 16.5 ± 1.5 | 3.12 ± 0.3 | 2.08 ± 0.5 |
| | HC | 9.6 ± 0.3 | 12.4 ± 1.8 | 15.7 ± 1.3 | 21.2 ± 1.4 | 3.65 ± 0.4 | 1.96 ± 0.4 |
| significance[e] | | | | | | | |
| genotype (G) | | * | * | * | * | * | ns |
| cultural system (C) | | * | * | * | * | ns | ns |
| G × C | | * | * | * | * | ns | ns |

[a] Data expressed as mean ± SEM. [b] Data expressed as micrograms of ellagic acid equivalents per gram of fresh weight. [c] Data expressed as micrograms of *p*-coumaric acid equivalents per gram of fresh weight. [d] Data expressed as micrograms of quercetin 3-glucoside equivalents per gram of fresh weight. [e] **, ns, significant or nonsignificant, respectively, at $p \leq 0.05$.

conditions (*41*, *42*). Among the plants grown in HC, fruit of Earliglow, Latestar, Mohawk, Redchief, B244-89, and MEUS 8 had higher amounts of ellagic acid than fruit of other cultivars. Redchief contained the highest amount of ellagic acid among those grown in MR, whereas B 28 contained the least (**Table 3**).

Twelve of 14 genotypes (all except Delmarvel and MEUS 8) had higher amounts of ellagic acid when grown in HC compared to in MR. The mean ellagic acid contents in strawberry juice were 8.1 and 9.6 $\mu$g/g of fresh wt for MR and HC, respectively. The content of ellagic acid glucoside in strawberry juice was higher than that of ellagic acid. Strawberry plants grown in HC in general had higher ellagic acid glucoside levels than those grown in MR. The genotypes with the highest ellagic acid glucoside content were Mohawk, MEUS 8, and Earliglow for those grown in HC and MR. B244-89 had the lowest ellagic acid glucoside content among all of the genotypes grown in MR. The mean ellagic acid glucoside contents were 9.6 and 12.4 $\mu$g/g of fresh wt for MR and HC, respectively.

The contents of *p*-coumaroylglucose, quercetin 3-glucoside, and quercetin 3-glucuronide varied substantially among the 14 cultivars and selections. In general, the contents of these flavonols were significantly higher than those of other flavonols, such as kaempferol 3-glucoside and kaempferol 3-glucuronide (**Table 3**). However, all of the flavonols are effective antioxidants (*43*). Kaempferol and quercetin are potent quenchers of $ROO^{\bullet}$, $O_2$, and $^1O_2$ (*44*). Quercertin and other polyphenols have been shown to play a protective role in carcinogenesis by reducing the bioavailability of carcinogens (*45*). Quercetin, with 3′,4′-dihydroxy substitution in the B-ring and conjugation between the A- and B-rings, has a high antioxidant potential (*46*). Kaempferol has a low antioxidant capacity against peroxyl radicals. The antioxidant capacities measured by the ORAC assay for quercetin and kaempferol are 3.29 and 2.67, respectively (*47*). Clegg and Morton **(***48*) reported that quercetin had the greatest antioxidant activity, followed by dihydroquercetin > kaempferol > quercitrin > chlorogenic acid = *p*-coumaric acid. Flavones in general have higher antioxidant activities compared to anthocyanins with the same hydroxylation patterns measured with the ORAC assay (*35*).

The anthocyanins are a group of flavonoids with exceptionally good scavenging activities. The antioxidant capacity of anthocyanins may be one of their most significant biological properties in humans (*12*). It has been shown that anthocyanins are strong antioxidants with free radical scavenging properties attributed to the phenolic hydroxyl groups attached to ring structures. Different hydroxylation and glycosylation may modulate their antioxidative properties (*49*−*52*). The anthocyanin cyanidin, with a 3′,4′-dihydroxy substitution in the B-ring and conjugation between the A- and B-rings, possesses a high antioxidant activity (*46*, *53*, *54*) and has antioxidant potentials 4 times that of Trolox (*50*). The antioxidant capacities measured

**Table 4.** Effect of Cultural Systems [Hill Plasticulture (HC) and Matted Row (MR)] on Cyanidin 3-Glucoside, Pelargonidin 3-Glucoside, Pelargonidin 3-Rutinoside, Cyanidin 3-Glucoside-succinate, and Pelargonidin 3-Glucoside-succinate Contents (Micrograms per Gram of Fresh Weight) in Fruit Juice of Various Strawberry Genotypes[a,b]

| genotype | cultural system | cyanidin 3-glucoside | pelargonidin 3-glucoside | pelargonidin 3-rutinoside | cyanidin 3-glucoside-succinate | pelargonidin 3-glucoside-succinate | pelargonidin derivative |
|---|---|---|---|---|---|---|---|
| Allstar | MR | 18.4 ± 0.3 | 365.3 ± 6.2 | | 13.6 ± 0.3 | 46.3 ± 2.5 | 1.8 ± 0.1 |
| | HC | 19.6 ± 0.4 | 393.8 ± 7.1 | | 15.1 ± 0.4 | 57.9 ± 2.8 | 2.9 ± 0.2 |
| Earliglow | MR | 54.5 ± 2.7 | 594.2 ± 5.2 | | 15.7 ± 0.1 | 163.5 ± 9.5 | |
| | HC | 66.7 ± 3.0 | 620.3 ± 6.5 | | 18.0 ± 0.2 | 206.6 ± 10.7 | |
| Delmarvel | MR | 16.0 ± 2.8 | 411.1 ± 2.3 | | 3.0 ± 0.1 | 61.9 ± 0.2 | 1.8 ± 0.1 |
| | HC | 27.9 ± 2.5 | 429.6 ± 4.6 | | 4.2 ± 0.1 | 63.4 ± 0.3 | 1.2 ± 0.1 |
| Latestar | MR | 17.1 ± 5.8 | 539.3 ± 1.3 | | 13.7 ± 1.2 | 6.3 ± 0.1 | 15.1 ± 1.8 |
| | HC | 44.5 ± 6.5 | 537.9 ± 1.4 | | 5.9 ± 1.5 | 57.9 ± 4.6 | 2.9 ± 0.7 |
| Lester | MR | 27.9 ± 0.7 | 626.0 ± 9.8 | | 12.8 ± 1.2 | 26.3 ± 3.7 | 12.1 ± 0.9 |
| | HC | 24.7 ± 0.6 | 677.9 ± 11.7 | | 19.0 ± 1.4 | 7.3 ± 1.6 | 17.1 ± 1.2 |
| Mohawk | MR | 26.7 ± 0.5 | 585.8 ± 6.5 | | 9.0 ± 2.1 | 147.3 ± 2.5 | |
| | HC | 29.9 ± 0.8 | 615.0 ± 7.2 | | 11.5 ± 2.4 | 159.9 ± 3.2 | |
| Northeaster | MR | 30.4 ± 2.1 | 662.6 ± 4.8 | 28.1 ± 1.9 | 6.7 ± 0.6 | 85.3 ± 1.7 | |
| | HC | 39.1 ± 2.2 | 683.0 ± 15.1 | 36.7 ± 2.1 | 9.7 ± 0.7 | 92.8 ± 1.8 | |
| Redchief | MR | 25.6 ± 1.1 | 556.7 ± 6.8 | | 10.1 ± 0.5 | 128.8 ± 6.5 | |
| | HC | 30.4 ± 1.2 | 585.1 ± 7.1 | | 12.6 ± 0.6 | 136.4 ± 7.8 | |
| B28 | MR | 31.6 ± 3.7 | 448.2 ± 21.6 | 20.3 ± 2.4 | 11.5 ± 1.5 | 90.6 ± 5.8 | |
| | HC | 51.1 ± 4.8 | 652.7 ± 25.5 | 34.6 ± 3.5 | 18.6 ± 1.7 | 263.8 ± 21.6 | |
| B35 | MR | 16.2 ± 1.5 | 418.7 ± 11.9 | 15.2 ± 0.3 | 2.1 ± 0.1 | 61.8 ± 0.2 | 0.5 ± 0.1 |
| | HC | 22.5 ± 1.6 | 470.4 ± 12.2 | 16.8 ± 0.4 | 2.3 ± 0.1 | 60.9 ± 0.2 | 2.9 ± 0.2 |
| B244-89 | MR | 37.7 ± 0.2 | 689.9 ± 3.5 | 32.1 ± 2.2 | 1.3 ± 0.1 | | 8.3 ± 0.7 |
| | HC | 39.0 ± 0.3 | 708.0 ± 4.2 | 43.0 ± 2.5 | 1.4 ± 0.1 | | 13.1 ± 1.2 |
| MEUS 8 | MR | 21.3 ± 1.8 | 324.2 ± 2.2 | 10.4 ± 1.5 | 13.2 ± 1.2 | 109.5 ± 7.5 | |
| | HC | 29.7 ± 2.0 | 337.0 ± 3.1 | 17.2 ± 1.7 | 19.7 ± 1.6 | 118.1 ± 8.4 | |
| MEUS 9 | MR | 31.8 ± 1.5 | 328.5 ± 4.3 | 10.7 ± 0.1 | 12.9 ± 0.4 | 158.0 ± 1.9 | |
| | HC | 38.6 ± 1.7 | 350.1 ± 5.2 | 11.3 ± 0.1 | 15.3 ± 0.5 | 166.5 ± 2.1 | |
| US 292 | MR | 31.4 ± 1.1 | 663.9 ± 7.3 | | 0.5 ± 0.1 | | 4.9 ± 0.9 |
| | HC | 36.6 ± 1.3 | 697.2 ± 8.2 | | 0.7 ± 0.1 | | 9.0 ± 1.3 |
| mean | MR | 27.6 ± 1.2 | 515.3 ± 5.6 | 19.4 ± 2.3 | 9.0 ± 0.5 | 90.5 ± 11.7 | 6.36 ± 1.2 |
| | HC | 35.7 ± 1.7 | 554.1 ± 7.2 | 26.6 ± 1.8 | 11.0 ± 1.2 | 116.0 ± 12.3 | 7.01 ± 1.1 |
| significance[c] | | | | | | | |
| genotype (G) | | * | * | * | * | * | * |
| cultural system (C) | | * | * | * | * | * | ns |
| G × C | | * | * | * | * | * | ns |

[a] Data expressed as mean ± SEM. [b] Data expressed as micrograms of cyanidin 3-glucoside equivalents per gram of fresh weight. [c] **, ns, significant or nonsignificant, respectively, at $p \leq 0.05$.

by ORAC assay for cyanidin 3-glucoside and pelargonidin 3-glucoside were found to be 2.24 and 1.54, respectively (*46*, *47*). The bright red color of strawberry fruit is due to their anthocyanin content. Two anthocyanidin glycosides, pelargonidin 3-glucoside and cyanidin 3-glucoside are almost exclusively responsible for the red color of strawberries (*55*). Strawberry fruit contained four major anthocyanins: cyanidin 3-glucoside, pelargonidin 3-glucoside, cyanidin 3-glucoside-succinate, and pelargonidin 3-glucoside-succinate (**Table 4**). The contents of cyanidin-based anthocyanins in strawberry fruit were much lower than those of pelargonidin-based anthocyanins (**Table 4**).

Comparison of the two cultural systems (HC and MR) showed that the main phenolic compounds, including anthocyanin pigments, present in strawberry juice had the same chemical components in both of the cultural systems, but there were significant quantitative differences. In general, phenolic acid and flavonol conents, as well as cyanidin-based and pelargonidin-based anthocyanins and total flavonoids, were greatest in the HC system. The mean values of *p*-coumaroylglucose, quercetin 3-glucoside plus quercetin 3-glucuronide, and kaempferol 3-glucoside for MR and HC were 10.9 and 15.7, 16.5 and 21.2, and 3.12 and 3.65 $\mu$g/g of fresh wt, respectively. The mean values of the anthocyanins cyanidin 3-glucoside, pelargonidin 3-glucoside, pelargonidin 3-rutinoside, cyanidin 3-glucoside-succinate, and pelargonidin 3-glucoside-succinate for MR and HC were 27.6 and 35.7, 515.3 and 554.1, 19.4 and 26.6, 9.0 and 11.0, and 90.5 and 116.0 $\mu$g/g of fresh wt, respectively. Fruit flavonol content in strawberry fruit was significantly greater in the HC system (**Tables 3**−**5**).

**Effect of Cultural Systems on Antioxidant Capacity in Strawberries.** The effects of cultural systems on ORAC against ROO$^\bullet$ in the juice of 14 strawberry genotypes were significant (**Table 5**). Strawberry grown in HC had significantly higher fruit ROO$^\bullet$ absorbance capacities. Plants grown in MR generally had low fruit ORAC values. In strawberry, the total antioxidant capacity values against ROO$^\bullet$ ranged from 11.9 to 17.8 $\mu$mol of Trolox/gof fresh wt (**Table 5**).

The sum of antioxidant activities of the individual phenolic compounds of strawberry juice which were separated by HPLC was much lower compared to the ORAC values of directly extracted strawberry juice (48.2 vs 73.9%) (**Table 5**). This unaccounted 51.8 to 36.1% antioxidant activity may have been due to unmeasured substances in the juice or synergistic interactions between the measured components. Thus, it seems that the antioxidant activity of individual phenolic compounds as well as synergistic and antagonistic effects together with other compounds present in the juice determines the total antioxidant activity of strawberries.

There was a linear correlation between total flavonoids and scavenging capacity of the ROO$^\bullet$ radical (ORAC) for strawberry juice. For example, the correlation coefficients between total flavonoids in strawberry juice and the ORAC values of directly extracted strawberry juice or the sum of ORAC values from the individual phenolic compounds of extracted strawberry juice

**Table 5.** Effect of Cultural Systems [Hill Plasticulture (HC) versus Matted Row (MR)] on ORAC Values in Fruit Juice of Various Strawberry Genotypes[a,b]

| genotype | cultural system | total flavonoids ($\mu$g/g of fresh wt) | ORAC value from direct extracted juice ($\mu$mol of TE/g of fresh wt) (A) | ORAC value in extracted juice after passing through $C_{18}$ Sep-Pak | | sum of ORAC values of individual flavonoid compound in juice after separation by HPLC | |
|---|---|---|---|---|---|---|---|
| | | | | $\mu$mol of TE/g of fresh wt | % of A | $\mu$mol of TE/g of fresh wt | % of A |
| Allstar | MR | 504.5 ± 15.9 | 11.9 ± 0.1 | 9.2 ± 0.1 | 77.0 | 6.4 ± 0.1 | 53.8 |
| | HC | 573.3 ± 17.1 | 12.5 ± 0.2 | 9.1 ± 0.1 | 72.8 | 6.5 ± 0.1 | 72.8 |
| Earliglow | MR | 909.6 ± 28.4 | 14.1 ± 0.4 | 12.1 ± 0.2 | 85.8 | 9.1 ± 0.2 | 64.5 |
| | HC | 1032.5 ± 29.1 | 17.8 ± 0.1 | 12.6 ± 0.2 | 70.8 | 11.8 ± 0.1 | 66.3 |
| Delmarvel | MR | 539.6 ± 15.2 | 12.1 ± 0.2 | 10.0 ± 0.1 | 82.6 | 6.2 ± 0.1 | 51.2 |
| | HC | 609.1 ± 16.7 | 13.8 ± 0.2 | 10.2 ± 0.1 | 73.9 | 6.6 ± 0.1 | 73.9 |
| Latestar | MR | 658.4 ± 18.1 | 12.0 ± 0.2 | 8.7 ± 0.1 | 72.5 | 6.5 ± 0.1 | 54.2 |
| | HC | 744.1 ± 20.4 | 12.8 ± 0.1 | 9.2 ± 0.2 | 71.9 | 8.5 ± 0.2 | 66.4 |
| Lester | MR | 779.4 ± 12.4 | 13.1 ± 0.2 | 10.0 ± 0.1 | 76.3 | 7.0 ± 0.2 | 53.4 |
| | HC | 841.3 ± 15.1 | 15.3 ± 0.1 | 11.1 ± 0.1 | 72.5 | 8.9 ± 0.3 | 58.2 |
| Mohawk | MR | 845.7 ± 15.5 | 13.5 ± 0.3 | 10.3 ± 0.2 | 76.3 | 8.8 ± 0.2 | 65.2 |
| | HC | 916.6 ± 17.2 | 14.6 ± 0.1 | 10.9 ± 0.2 | 74.7 | 9.6 ± 0.3 | 65.8 |
| Northeaster | MR | 901.4 ± 15.2 | 13.8 ± 0.4 | 10.9 ± 0.1 | 79.0 | 9.0 ± 0.1 | 65.2 |
| | HC | 966.4 ± 16.1 | 15.8 ± 0.5 | 11.9 ± 0.3 | 75.3 | 10.1 ± 0.3 | 63.9 |
| Redchief | MR | 806.0 ± 10.8 | 13.9 ± 0.2 | 11.5 ± 0.1 | 82.7 | 7.9 ± 0.1 | 56.8 |
| | HC | 857.6 ± 11.7 | 14.8 ± 0.2 | 11.4 ± 0.0 | 77.0 | 8.6 ± 0.2 | 58.1 |
| B 28 | MR | 654.1 ± 18.5 | 13.9 ± 0.3 | 10.3 ± 0.1 | 74.1 | 6.7 ± 0.1 | 48.2 |
| | HC | 1133.6 ± 23.4 | 17.7 ± 0.9 | 13.4 ± 0.3 | 75.7 | 11.0 ± 0.3 | 62.1 |
| B 35 | MR | 576.8 ± 16.3 | 10.3 ± 0.3 | 8.4 ± 0.1 | 81.6 | 6.6 ± 0.1 | 64.1 |
| | HC | 646.6 ± 17.2 | 12.1 ± 0.1 | 9.2 ± 0.1 | 76.0 | 6.7 ± 0.1 | 55.4 |
| B244-89 | MR | 823.1 ± 10.7 | 13.2 ± 0.2 | 11.7 ± 0.2 | 88.6 | 8.8 ± 0.2 | 66.7 |
| | HC | 874.1 ± 12.5 | 14.3 ± 0.3 | 10.3 ± 0.1 | 72.0 | 8.8 ± 0.2 | 61.5 |
| MEUS 8 | MR | 530.1 ± 12.0 | 11.1 ± 0.3 | 10.0 ± 0.0 | 90.0 | 6.3 ± 0.1 | 56.8 |
| | HC | 590.3 ± 13.5 | 12.8 ± 0.2 | 10.1 ± 0.1 | 78.9 | 6.4 ± 0.1 | 50.0 |
| MEUS 9 | MR | 578.6 ± 9.71 | 11.3 ± 0.2 | 9.1 ± 0.0 | 80.5 | 5.6 ± 0.1 | 49.6 |
| | HC | 625.5 ± 11.2 | 13.0 ± 0.3 | 9.1 ± 0.0 | 70.0 | 6.7 ± 0.2 | 51.5 |
| US 292 | MR | 767.4 ± 12.7 | 12.7 ± 0.2 | 10.3 ± 0.1 | 81.1 | 7.6 ± 0.2 | 59.8 |
| | HC | 831.3 ± 15.4 | 13.9 ± 0.1 | 10.8 ± 0.2 | 77.7 | 8.5 ± 0.1 | 61.2 |
| mean | MR | 705.3 ± 12.3 | 12.6 ± 0.2 | | | | |
| | HC | 803.0 ± 8.91 | 14.4 ± 0.3 | | | | |

[a] Data expressed as mean ± SEM. [b] Data expressed as micromoles of Trolox equivalents per gram of fresh weight.

were 0.867 and 0.950, respectively. When the antioxidant activity of extracted strawberry juices was measured with a $C_{18}$ Sep-Pak column and recovered with acidified MeOH, the ORAC value of this fraction contained 70.8−90.0% of the total antioxidant activity of the original juice extracted (**Table 5**). This suggests that some water-soluble constituents of strawberry juice passing through the $C_{18}$ Sep-Pak also possess antioxidant activity. Sugars, acids, ascorbic acid, gallic acid, glutathione, and other water-soluble compounds are removed and not retained in the $C_{18}$ Sep-Pak column. Sugars and organic acids showed no antioxidant activity with the DPPD, FRAP, and TEAC methods (*56*, *57*). However, citric, malic, and tartaric acids showed antioxidant activity when the DMPD method was tested (*56*). We also found no antioxidant activity of sugars and citric acid with the ORAC assay (data not shown). However, gallic acid, ascorbic acid, and glutathione exhibited inhibition of peroxyl radical induced PE oxidation in our ORAC assay. The ORAC values for gallic acid, ascorbic acid, and glutathione were 1.74, 0.69, and 0.74, respectively. Cao and Prior (*58*) also showed gallic acid, ascorbic acid, and glutathione antioxidant activity using the ORAC method.

**Relative Contribution of Antioxidant Substances to the Total Antioxidant Activity of Strawberry Juice.** Different flavonoids were present in strawberry juice. To calculate their relative contribution of antioxidant activity to the total antioxidant activity of the juices, the relative antioxidant activity of each compound was measured and expressed as a percentage of the total antioxidant activity (**Table 6**). For example, in B 28, the ORAC value for cyanidin 3-glucoside was 1.37 $\mu$mol of TE/g of fresh wt, and therefore the antioxidant capacity contributed by cyanidin 3-glucoside to the total antioxidant capacity was calculated to be 13.3% for HC-grown fruit. Cyanidin 3-glucoside in strawberries from MR contributed only 10.6%. Pelargonidin 3-glucoside was the predominant anthocyanin in the strawberry juice in all 14 strawberry genotypes. Pelargonidin 3-glucoside in MR- and HC-grown strawberries contributed 27.1 and 27.3%, respectively, to the total antioxidant

**Table 6.** Effect of Cultural Systems [Hill Plasticulture (HC) versus Matted Row (MR)] on ORAC Values of Different Flavonoids in Strawberry (Genotype B-28)[a]

| flavonoid | ORAC ($\mu$mol TE/g of fresh wt)[a] | | ORAC (%) | |
|---|---|---|---|---|
| | MR | HC | MR | HC |
| *p*-coumaroylglucose | 0.697 | 0.985 | 10.47 | 9.61 |
| dihydroflavonol | 0.547 | 0.525 | 8.23 | 5.11 |
| ellagic acid | 0.150 | 0.261 | 2.25 | 2.54 |
| quercetin 3-glucoside and 3-glucuronide | 0.645 | 0.708 | 9.69 | 6.91 |
| kaempferol 3-glucoside | 0.309 | 0.355 | 4.64 | 3.47 |
| kaempferol 3-glucuronide | 0.284 | 0.463 | 4.27 | 4.51 |
| cyanidin 3-glucoside | 0.706 | 1.365 | 10.62 | 13.31 |
| pelargonidin 3-glucoside | 1.801 | 2.80 | 27.08 | 27.31 |
| pelargonidin 3-rutinoside | 0.550 | 0.866 | 8.27 | 8.45 |
| cyanidin 3-glucoside-succinate | 0.224 | 0.567 | 3.36 | 5.53 |
| pelargonidin 3-glucoside-succinate | 0.739 | 1.358 | 1.11 | 13.25 |
| total | 6.651 | 10.253 | 100.00 | 100.00 |

[a] Data expressed as micromoles of Trolox equivalents per gram of fresh weight.

capacity measured with the ORAC assay. *p*-Coumaroylglucose and ellagic acid together constituted 12.7% of the total antioxidant activity of strawberry juice. Kaempferol 3-glucoside and kaempferol 3-glucuronide constituted 4.6 and 4.3%, respectively, of the total antioxidant activity, whereas pelargonidin 3-rutinoside constituted 8.3%. In fruits of other genotypes, pelargonidin 3-glucoside generally contributed ~26.0−28.0% of the total antioxidant capacity (data not shown).

Collectively, the data presented here indicate that different cultural systems (HC vs MR) significantly affect strawberry fruit quality, as does genotype. Fruit from the HC system had higher soluble solids content, total sugars, fructose, glucose, ascorbic acid, titratable acid, citric acid, and flavonoid contents and antioxidant capacities than fruits grown in the MR system.

## ABBREVIATIONS USED

AAPH, 2′,2′-azobis(2-amidinopropane) dihydrochloride; ORAC, oxygen radical absorbance capacity; R-PE, (*R*)-phycoerythrin; Trolox, 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid; TE, Trolox equivalents.

## LITERATURE CITED


(1) Cannell, G. H.; Voth, V.; Bringhurst, R. S.; Proebsting, E. L. The influence of irrigation levels and application methods, polyethylene mulch and nitrogen fertilization on strawberry production in Southern California. *Proc. Am. Soc. Hortic. Sci.* **1961**, *28*, 281−291.

(2) Locascio, S. J.; Smart, G. C., Jr. Influence of polyethylene mulch colors and soil fumigants on strawberry production. *Proc. Fla. State. Hortic. Soc.* **1968**, *81*, 147−153.

(3) Baumann, T. E.; Eaton, G. W.; Machholz, A.; Spaner, D. Day-neutral strawberry production on raised beds in British Columbia. *Adv. Strawberry Res*. **1995**, *14*, 53−57.

(4) Himelrick, D. G. Effect of polyethylene mulch color on soil temperatures and strawberry plant response. *Adv. Strawberry Prod*. **1982**, *1*, 15−16.

(5) Scheel, D. C. The effect of clear polyethylene winter mulch on the growth and yield of strawberries. *Adv. Strawberry Prod*. **1982**, *1*, 29−30.

(6) Ames, B. M.; Shigena, M..K.; Hagen, T. M. Oxidants, antioxidants and the degenerative diseases of aging. *Proc. Natl. Acad. Sci. U.S.A.* **1993**, *90*, 7915−7922.

(7) Ascherio, A.; Rimm, E. B.; Giovannucci, E. L.; Colditz, G. A.; Rosner, B.; Willett, W. C.; Sacks, F.; Stampfer, M. J. A prospective study of nutritional factors and hypertension among US men. *Circulation* **1992**, *86*, 1475−1484.

(8) Cao, G.; Sofic, E.; Prior, R. L. Antioxidant capacity of tea and common vegetables. *J. Agric. Food Chem.* **1996**, *44*, 3426−3441.

(9) Dragsted, L. O.; Strube, M.; Larsen, J. C. Cancer-protective factors in fruits and vegetables: biochemical and biological background. *Pharmacol. Toxicol*. **1993**, *72* (Suppl. 1), 116−135.

(10) Gey, K. F. The antioxidant hypothesis of cardiovascular disease: epidemiology and mechanisms. *Biochem. Soc. Trans.* **1990**, *18*, 1041−1045.

(11) Velioglu, Y. S.; Mazza, G.; Gao, L.; Oomah, B. D. Antioxidant activity and total phenolics in selected fruits, vegetables, and grain products. *J. Agric. Food Chem.* **1998**, *46*, 4113−4117.

(12) Wang, H.; Cao, G.; Prior, R. L. Total antioxidant capacity of fruits. *J. Agric. Food Chem*. **1996**, *44*, 701−705.

(13) Wang, S. Y.; Jiao, H. Scavenging capacity of berry crops on superoxide radicals, hydrogen peroxide, hydroxyl radicals, and singlet oxygen. *J. Agric. Food Chem*. **2000**, *48*, 5677−5684.

(14) Wang, S. Y.; Lin, H. S. Antioxidant activity in fruit and leaves of blackberry, raspberry, and strawberry varies with cultivar and developmental stage. *J. Agric. Food Chem.* **2000**, *48*, 140−146.

(15) Lundergan, C. A.; Moore, J. N. Inheritance of ascorbic acid content and color intensity in fruits of strawberry (*Fragaria* × *ananassa* Duch.). *J. Am. Soc. Hortic. Sci.* **1975**, *100*, 633−635.

(16) Wang, S. Y.; Ji, Z. L.; Faust, M. Metabolic changes associated with bud break induced by thidiazuron. *J. Plant Growth Regul.* **1987**, *6*, 85−95.

(17) Cao, G.; Alessio, H. M.; Culter, R. G. Oxygen-radical absorbance capacity assay for antioxidants. *Free Radical Biol. Med*. **1993**, *14*, 303−311.

(18) NCSS 97. *Statistical System for Windows*; Kaysville, UT, 1997.

(19) Kader, A. A. Quality and its maintenance to the postharvest physiology of strawberry. In *The Strawberry Into the 21st Century*; Dale, A., Luby, J. J., Eds.; Proceedings of the Third North American Strawberry Conference, Houston, TX; Timber Press: Portland, OR, 1990; pp 145−152.

(20) Galletta, G. J.; Maas, J. L.; Enns, J. M.; Draper, A. D.; Swartz, H. J. 'Mohawk' strawberry. *HortScience* **1995**, *30*, 631−634.

(21) Shaw, D. V. Genotypic variation and genotypic correlations for sugars and organic acids in strawberries. *J. Am. Soc. Hortic. Sci.* **1990**, *115*, 839−843.

(22) Halpner, A. D.; Handelman, G. J.; Belmont, C. A.; Harris, J. M.; Blumberg, J. B. Prodection by vitamin C of oxidant-induced loss of vitamin E in rat hepatocytes. *J. Nutr. Biochem*. **1998**, *9*, 355−359.

(23) Jacob, R. A. The integrated antioxidant system. *Nutr. Res.* **1995**, *15*, 755−766.

(24) Buettner, G. R. The pecking order of free radicals and antioxidants: lipid peroxidation, α-tocopherol, and ascorbate. *Arch. Biochem. Biophys*. **1993**, *300*, 535−543.

(25) Delamere, N. A. Ascorbic acid and the eye. *Subcell. Biochem.* **1996**, *25*, 313−329.

(26) Frei, B. T.; England, L.; Ames, B. N. Ascorbate is an outstanding antioxidant in human blood plasma. *Proc. Natl. Acad. Sci. U.S.A.* **1989**, *86*, 6377−6381.

(27) Jialal, I.; Vega, G. I.; Grundy, S. M. Physical levels of ascorbate inhibit the oxidative modification of low-density lipoprotein. *Atherosclerosis* **1990**, *82*, 185−191.

(28) Tsao, C. S. An overview of ascorbic acid chemistry and biochemistry. In *Vitamin C in Health and Disease*; Packer, L., Fuchs, J., Eds.; Dekker: New York, 1997; pp 25−58.

(29) Weisburger, J. H. Nutritional approach to cancer prevention with emphasis on vitamins, antioxidants and carotenoids. *Am. J. Clin. Nutr.* **1991**, *53*, 226S−237S.

(30) Forney, C. F.; Breen, P. J. Collection and characterization of phloem exudate from strawberry pedicels. *HortScience* **1985**, *20*, 413−414.

(31) Doty, T. E. Fructose sweetness: A new dimension. *Cereal Foods World* **1976**, *21*, 62−63.

(32) Pangborn, R. M. Relative taste intensities of selected sugars and organic acids. *J. Food Sci.* **1953**, *28*, 726−733.

(33) Yamaguchi, S.; Yoshikawa, T.; Ikeda, S.; Ninomiya, T. Studies on the taste of some sweet substances. Part I. Measurement of the relative sweetness. *Agric. Biol. Chem.* **1970**, *34*, 181−186.

(34) Kuehnau, J. The flavonoids. A class of semi-essential food components: their role in human nutrition. *World Rev. Nutr. Diet* **1976**, *24*, 117−191.

(35) Bors, W.; Heller, W.; Michel, S.; Saran, M. Flavonoids as antioxidants: determination of radical scavenging efficiencies. *Methods Enzymol*. **1990**, *186*, 343−355.

(36) Amiot, M. J.; Tacchini, M.; Aubert, S. Y.; Oleszek, W. Influence of cultivar, maturity stage, and storage conditions on phenolic composition and enzymatic browning of pear fruits. *J. Agric. Food Chem*. **1995**, *43*, 1132−1137.

(37) Heinonen, I. M.; Meyer, A. S.; Frankel, E. N. Antioxidant activity of berry phenolics on human low-density lipoprotein and liposome oxidation. *J. Agric. Food Chem*. **1998**, *46*, 4107−4112.

(38) Daniel, E. M.; Krupnick, A. S.; Heur, Y. H.; Blinzler, J. A.; Nims, R. W.; Stoner, G. D. Extraction, stability, and quantification of ellagic acid in various fruits and nuts. *J. Food Chem. Compos. Anal*. **1989**, *2*, 338−349.

(39) Maas, J. L.; Galletta, G. J.; Stoner, G. D. Ellagic acid, an anticarcinogen in fruits, especially in strawberries: a review. *HortScience* **1991**, *26*, 10−14.

(40) Okuda, T.; Yoshida, T.; Hatano, T. Ellagitannins as active constituents of medical plants. *Planta Med.* **1989**, *55*, 117−122.
(41) Maas, J. L.; Wang, S. Y.; Galletta, G. J. Evaluation of strawberry cultivars for ellagic acid content. *HortScience* **1991**, *26*, 66−68.
(42) Wang, S. Y.; Maas, J. L.; Payne, J. A.; Galletta, G. J. Ellagic acid content in small fruits, mayhaws, and other plants. *J. Small Fruit Vitic.* **1994**, *2*, 39−49.
(43) Pratt, D. E. Natural antioxidants from plant material. *ACS Symp. Ser.* **1992**, *No. 507*, 54−71.
(44) Larson, R. A. The antioxidants of higher plants. *Phytochemistry* **1988**, *27*, 969−978.
(45) Starvic, B.; Matula, T. I.; Klassen, R.; Downie, R. H.; Wood, R. J. Effect of flavonoids on mutagenicity and bioavailability of xenobiotics in food. In *Phenolic Compounds in Food and Their Effects on Health II. Antioxidants and Cancer Prevention*; Huang, M. T., Ho, C. T., Lee, C. Y., Eds.; ACS Symposium Series 507; American Chemical Society: Washington, DC, 1992; pp 239−249.
(46) Ratty, A. K.; Das, N. P. Effects of flavonoids on non-enzymic lipid peroxidation: structure activity relationship. *Biochem. Med. Metab. Biol*. **1988**, *39*, 69−79.
(47) Cao, G.; Sofic, E.; Prior, R. L. Antioxidant and prooxidant behavior of flavonoids: Structure-activity relationships. *Free Radicals Biol. Med*. **1997**, *22*, 749−760.
(48) Clegg, K. M.; Morton, A. D. The phenolic compounds of blackcurrant juice and their protective effect on ascorbic acid. II. The stability of ascorbic acid in model systems containing some of the phenolic compounds associated with black currant juice. *J. Food Technol.* **1968**, *3*, 277−284.
(49) Rice-Evans, C. A.; Miller, N. J. Antioxidant activities of flavonoids as bioactive components of food. *Biochem. Soc. Trans*. **1996**, *24*, 790−795.
(50) Rice-Evans, C. A.; Miller, N. J.; Bolwell, P. G.; Bramley, P. M.; Pridham, J. B. The relative antioxidant activities of plant-derived polyphenolic flavonoids. *Free Radical Res.* **1995**, *22*, 375−383.
(51) Yoshiki, Y.; Okubo, K.; Igarashi, K. Chemiluminescence of anthocyanins in the presence of acetaldehyde and *tert*-butyl hydroperoxide. *J. Biolumin. Chemilumin*. **1995**, *10*, 335−338.
(52) Wang, H.; Cao, G.; Prior, R. L. Oxygen radical absorbing capacity of anthocyanins. *J. Agric. Food Chem*. **1997**, *45*, 304−309.
(53) Rajalakshmi, D.; Narasimhan, S. Food antioxidants: Sources and methods of evaluation. In *Food Antioxidants*; Madhavi, D. L., Deshpande, S. S., Salunkhe, D. K., Eds.; Dekker: New York, 1996; pp 65−83.
(54) Dziedzic, S. Z.; Hudson, B. J. F. Polyhydroxy chalcones and flavanones as antioxidants for edible oils. *Food Chem.* **1983**, *12*, 205−212.
(55) Timberlake, C. F.; Bridle, P. Distribution of anthocyanins in food plant. In *Anthocyanins as Food Colors*; Academic Press: New York, 1982; 137 pp.
(56) Gil, M. I.; Tomás-Barberán, F. A.; Hess-Pierce, B.; Holcroft, D. M.; Kader, A. A. Antioxidant activity of pomegranate juice and its relationship with phenolic composition and processing. *J. Agric. Food Chem*. **2000**, *48*, 4581−4589.
(57) Lea, A. G. H. Apple juice. In *Production of Non-Carbonated Fruit Juices and Beverages*; Hicks, D., Ed.; Blackie: Glasgow, Scotland, 1991; pp 182−225.
(58) Cao, G.; Prior, R. L. The measurement of oxygen radical absorbance capacity in biological samples. *Methods Enzymol*. **1999**, *299*, 50−62.

**Received for review May 30, 2002. Revised manuscript received August 15, 2002. Accepted August 15, 2002.**

JF020614I