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Response of Citrus Fruit to High-pressure Washing

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Abstract. The effect of high-pressure washing (HPW) on the surface morphology and physiology of citrus fruit was examined. Mature white (*Citrus paradisi* Macf. 'Marsh') and red (*Citrus paradisi* Macf. 'Ruby Red') grapefruit, oranges (*Citrus sinensis* L. 'Hamlin'), and tangelos (*Citrus reticulata* Blanco x *Citrus paradisi* Macf. 'Orlando') were washed on a roller brush bed and under a water spraying system for which water pressure was varied. Washing white grapefruit and oranges for 10 seconds under conventional low water pressure (345 kPa at cone nozzle) had little effect on peel wax fine structure. Washing fruit for 10 seconds under high water pressure (1380 or 2760 kPa at veejet nozzle) removed most epicuticular wax platelets from the surface as well as other surface debris such as sand grains. Despite the removal of epicuticular wax, HPW did not affect whole fruit mass loss or exchange of water, O_2, or CO_2 at the midsection of the fruit. Analysis of the effect of nozzle pressure (345, 1380, or 2760 kPa), period of exposure (10 or 60 seconds), and wax application on internal gas concentrations 18 hours after washing showed that increasing nozzle pressure increased internal CO_2 concentrations while waxing increased internal ethylene and CO_2 concentrations and decreased O_2 concentrations. An apparent wound ethylene response was often elicited from fruit washed under high pressures (≥2070 kPa) or for long exposure times (≥30 seconds).

Citrus fruit are routinely washed on brushes with a surfactant solution to remove dirt, superficial molds, scale, and spray residues from the peel surface. High-pressure washing (HPW) systems facilitate the cleaning process by using the force of water to dislodge surface material. While HPW has been available for many years (Kaplan, 1986), recent technological improvements in commercially available systems have increased its usage among citrus packers (Katz, 1995).

The effect of conventional low-pressure washing on citrus physiology has been examined previously. Washing has been shown to increase the rate of water loss (Hagenmaier and Baker, 1993; Millier and Brown, 1973) and degreening time (Grierson and Newhall, 1956) and stimulate apparent wound responses, such as increased internal concentrations (Vines and Oberbacher, 1961) and evolution rates (Parker et al., 1984) of CO_2. Washing may also affect the development of citrus peel disorders. Spotting and zebra-skin development of mandarins (*Citrus reticulata* Blanco) may be caused by washing with firm-bristled brushes (Amat, 1988). Washing has been shown to increase (Smoot et al., 1971) and reduce (Chace et al., 1969) the occurrence of aging, a peel disorder similar to stem end rind breakdown. Stem end rind breakdown itself may be induced by excessive water loss (Albrigo, 1972), and thus, may also be stimulated by washing.

The physiological response of citrus fruit to HPW has not been previously documented. Tidwell et al. (1997) showed that HPW improved puree quality of clingstone peaches (*Prunus persica* (L.) Batsh. 'Allgold') by removing decayed matter from the fruit surface, but reported no negative effects. Commercial HPW of citrus fruit may disrupt the peel of rotted or physically weakened fruit, but it typically causes no visible damage to sound fruit. The effectiveness of HPW in removing superficial molds and scale suggests that the peel may be affected in less obvious ways such as by accelerating water loss during storage. Moreover, the physical impact of HPW has raised concerns of a wound response. Therefore these studies were undertaken to develop an understanding of effects of HPW on citrus fruit. Specifically, we examined the effects of washing on surface morphology, gas exchange, and internal concentrations of ethylene, O_2, and CO_2.

Materials and Methods

Plant material. Mature 'Marsh' white grapefruit and 'Orlando' tangelos were harvested at the Citrus Research and Education Center (CREC) in Lake Alfred, Fla. Mature 'Ruby Red' grapefruit and 'Hamlin' oranges were obtained through a local commercial packinghouse. Harvest dates are listed below. Fruit were degreened only when noted. Fruit diameters were 10 to 13 cm for white and red grapefruit, 9 to 11 cm for oranges, and 7 to 9 cm for tangelos.

HPW system. All fruit were washed at FMC in Lakeland, Fla. The HPW system consisted of four banks of veejet nozzles that

Table 1. Average impact pressure for the five nozzle pressure and flow rate combinations used in this study.

Nozzle pressure (kPa)	Flow rate ($L \cdot min^{-1}$)	Nozzle type	Nozzle distance to brush valley (cm)	Avg impact pressure (kPa)[z]
345	5.2	Cone	31	0.8
1380	5.7	Veejet	23	2.8
2070	6.9	Veejet	23	4.1
2760	8.3	Veejet	23	5.8
3450	9.5	Veejet	23	7.4

[z]Average impact pressure was calculated from Eq. [1] for the minimum distance between the nozzle and a 12-cm-diameter fruit.

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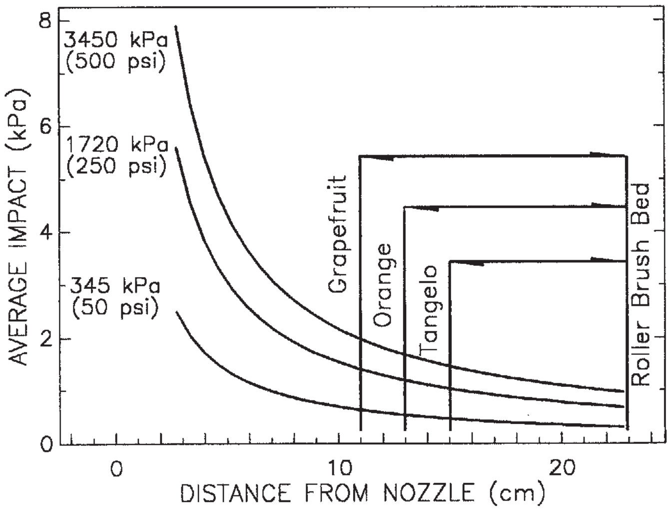


Fig. 1. Effect of nozzle pressure (345, 1720, and 3450 kPa) and distance from nozzle on the theoretical average spray impact pressure for a veejet nozzle (Eq. [1]).

extended from a manifold. The banks were spaced 20 cm apart, and three or four nozzles were on each bank. The nozzles were spaced 15 cm apart along each bank and positioned 23 cm above a bed of rotating brushes. The brushes consisted of x-shaped low density polyethylene bristles 0.56 mm in diameter (East Coast citrus brush type with 0.022 PEX bristles, Industrial Brush Corp., Pomona, Calif.). Brushes were run at 2 revolutions/s.

The elliptical spray plume of the nozzle was aligned to run between and parallel to the brushes. Spray plumes of adjacent nozzles overlapped ≈2 cm between brush valleys of the brush bed. Fruit were placed directly under the nozzles during washing. The minimum distances between the nozzle outlet and top of the fruit were ≈11, 13, and 15 cm for white or red grapefruit, orange, and tangelo, respectively. Nozzle pressures of 1380, 2070, 2760, and 3450 kPa (200, 300, 400, and 500 psi, respectively) with corresponding flow rates of 5.7, 6.9, 8.3, and 9.5 $L \cdot min^{-1}$ were attained by adjusting the pump output (Table 1). Conventional low pressure washing was simulated in the same brushing system. Four banks of cone nozzles extended from a manifold. The banks were spaced 20 cm apart, and three nozzles were on each bank. The nozzles were spaced 12 cm apart and positioned 31 cm above the brush bed. Nozzle pressure for low pressure washing was 345 kPa with a corresponding flow rate of 5.2 $L \cdot min^{-1}$.

The theoretical average impact pressure, as derived from Bernoulli's principle (Sakiadis, 1984; Sears et al., 1979), is proportional to the flow rate and the square root of the nozzle pressure and is inversely proportional to the distance from the nozzle (Spraying Systems Co., 1989):

$$\text{Average impact pressure} = (\sqrt{\text{nozzle pressure}} \times \text{flow rate} \times \text{conversion factor})/\text{distance from nozzle} \quad [1]$$

The conversion factor accounts for nozzle characteristics (e.g., plume shape and impact efficiency) and unit conversions. Figure 1 illustrates the effect of nozzle pressure and distance from nozzle on average impact for a 40% veejet nozzle positioned 23 cm above the brush bed. Since the nozzle to fruit distance decreases with increasing fruit size, the average impact pressure is ≈36% greater for a 12-cm grapefruit than for a 8-cm tangelo when flow rate and nozzle pressure are constant. In comparison, impact pressure increases ≈41% when the nozzle pressure is doubled from 1720 to 3450 kPa and flow rate and distance from nozzle are constant. The calculated average impact pressure on a 12-cm grapefruit for the five nozzle pressure and flow rate settings used in these studies are listed in Table 1. Although impact force is a function of flow rate, distance from nozzle, and nozzle type as well as nozzle pressure, spray treatments have been designated by the nozzle pressure.

Gas exchange measurement. Water, O_2, and CO_2 exchange through the peel at the mid- section of the fruit was measured by a system described previously (Petracek, 1995). Mass loss was determined for fruit held at 23 %C and 45% relative humidity (RH). Fruit were individually weighed at the beginning and end of a 30 min period. Rate of mass loss was expressed as the change in mass divided by the initial mass divided by the time between mass measurements.

Measurement of internal ethylene, O_2, and CO_2 concentrations. Silicone (≈1 cm in diameter and 0.3 cm thick) was applied to the stylar end of the fruit of all four citrus varieties to create a gas sampling septum. Internal gas samples (0.5 mL) were taken from the fruit core through the septum by an insulin syringe equipped with a 7-mm needle. Samples were analyzed by a flow-through system consisting of the O_2 and CO_2 analyzers (Petracek, 1995) connected in series with N_2 used as the carrier gas. Ethylene was analyzed by a GC (5709A, Hewlett Packard, Wilmington, Del.) equipped with an activated alumina column and a flame ionization detector.

Effect on morphology. The effect of washing on surface morphology was evaluated only for white grapefruit and oranges harvested on 19 Jan. 1995. Fruit were either not washed or washed for 10 s under low (345 kPa) or high pressure (1380 or 2760 kPa). Fruit peel disks (6 mm in diameter and 3 to 4 mm thick) were excised from fruit with a cork borer within 3 h after washing. Disks were placed in petri dishes and transferred to a freezer (–40 °C) and held until further processing. The frozen disks were placed in precooled copper wire baskets, submerged in liquid nitrogen, and freeze dried for 24 to 48 h. The disks were then mounted on stubs, sputter-coated with gold-palladium, and examined under a scanning electron microscope (model S-530; Hitachi Instruments, Inc., San Jose, Calif.) operating at 20 kV. At least three disks per fruit and three fruit per treatment were examined. A second set of disks was carbon coated and examined by the scanning electron microscope and a X-ray detector (Kevex 8005; Fisons Instruments, San Carlos, Calif.). Disks from a minimum of three fruit per treatment were examined.

Effect on gas exchange. Two studies were performed to assess the effect of washing on gas exchange. In the first study, the effects of washing and surfactant treatment on mass loss and on water, CO_2, and O_2 exchange were determined for only white grapefruit using fruit harvested and treated on 19 Jan. 1995. Surfactant treated fruit were first washed for 30 s on roller brushes coated with 0.05% (w/v) cleaning solution containing anionic and nonionic surfactants (Fruit Cleaner 395; FMC, Lakeland, Fla.). Fruit were then either not washed or washed for 10 s under 345, 1380, or 2760 kPa pressure. Nonsurfactant treated fruit were similarly not washed or washed. Fruit were transported to the CREC and held at 24 ± 1 °C and 50% ± 5% RH within 60 min after washing. Mass loss was determined at 3 and 14 h, and gas exchange was measured between 15 and 22 h after washing. Ten fruit were used per treatment. Data were organized in a completely randomized factorial design and analyzed by analysis of variance (ANOVA) using PlotIt (Scientific Programming Enterprise, Haslett, Mich.). Unless otherwise noted, only data significant at $P \leq 0.05$ are discussed in this and subsequent experiments.

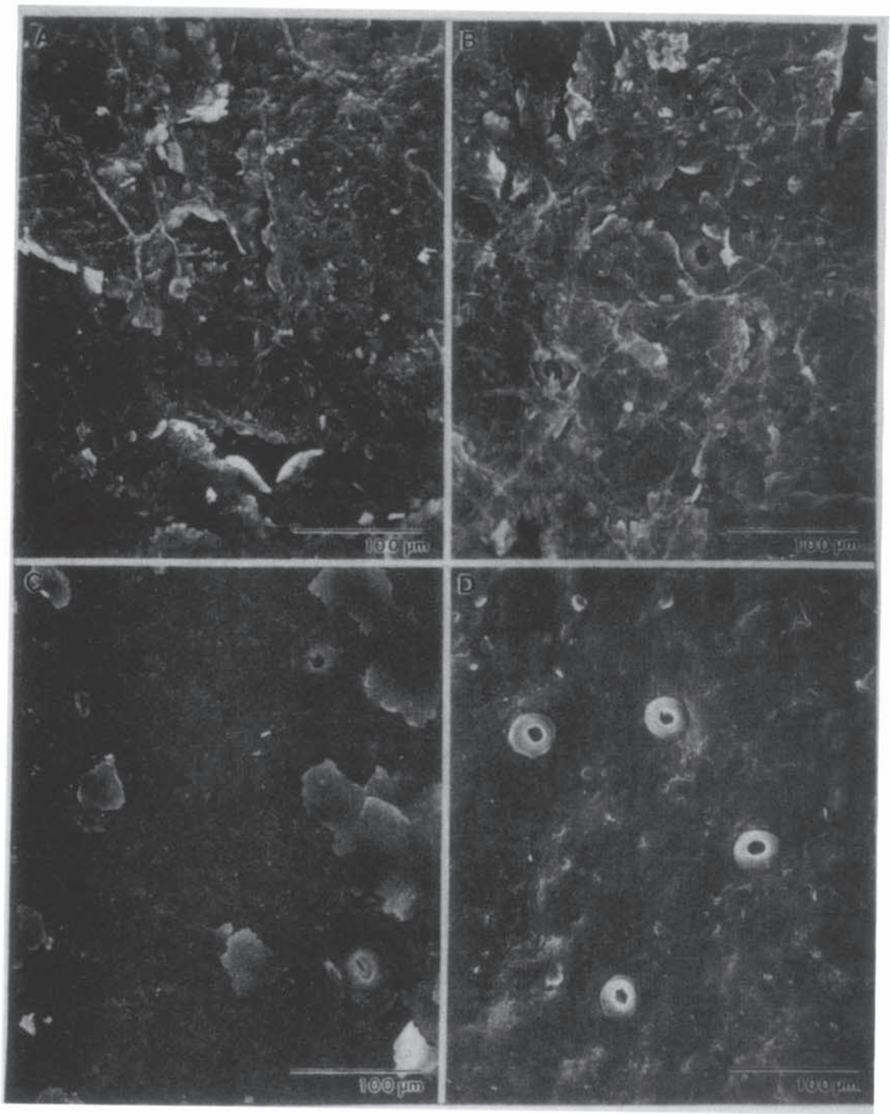
In the second study, the effect of washing on mass loss was determined for only white grapefruit and oranges. Fruit were harvested on 20 Nov. 1995, and the initial rate of mass loss was measured within 2 h after harvest. Fruit were then either not washed or placed on rollers without water for 10 s, or washed for 10 s under 345, 1380, or 2760 kPa pressure. Fruit were transported to the CREC and held at 24 ± 1 °C and 45% ± 5% RH within 60 min after washing. Mass loss was determined at 3, 6, and 20 h after washing. Ten fruit were used per treatment. Data were organized in a completely randomized design and analyzed by ANOVA.

Effect on internal gas composition. The effect of nozzle pressure, period of washing exposure, and wax application on internal gas composition was measured for only white grapefruit. Fruit were harvested on 30 Dec. 1994. Internal ethylene, O_2, and CO_2 concentrations were measured prior to washing. Fruit were washed for 10 or 60 s under low (345 kPa) or high (1380 or 2760 kPa) pressure. Fruit were transported to the CREC and were either not coated or coated with a commercially available shellac-based water wax (FMC, Lakeland, Fla.) between 45 and 60 min after washing. Fruit were held at 24 ± 1 °C and 50% ± 5% RH and sampled for internal gas level beginning at 3, 9, 18, 45, and 144 h after washing. Each gas sampling period required ≈2 h to complete. Six fruit were used per treatment. Data were organized in a completely randomized factorial design and analyzed by ANOVA.

The effect of nozzle pressure and period of exposure to HPW on internal gas level was measured for all four varieties. Red grapefruit were harvested on 12 Dec. 1994, degreened (5 $\mu L \cdot L^{-1}$ ethylene, 29 °C, and 95% RH) for 48 h, and degassed (0 $\mu L \cdot L^{-1}$ ethylene, 21 °C, and 95% RH) for 24 h. Oranges were harvested on 11 Dec. 1994, degreened for 60 h, and degassed for 24 h. White grapefruit and tangelos were harvested on 15 Dec. 1994 and were not degreened. Fruit were washed for 10, 20, 30, 60, or 120 s under 345, 1380, 2070, 2760, or 3450 kPa pressures on 15 Dec. 1994. Fruit were transported to the CREC and held at 21 ± 1 °C and 93% ± 3% RH. Internal ethylene, O_2, and CO_2 concentrations were measured 24 h after washing. Five fruit were used per treatment. Data were organized in a completely randomized design. The effects of nozzle pressure and period of exposure on internal O_2 and CO_2 concentrations were determined by multiple linear regression for each variety.

The effects of HPW in a local commercial packinghouse was evaluated. Red grapefruit were harvested on 11 Jan. 1995 from a central Florida grove. Fruit were divided into three sets of 50 fruit each. Fruit were either washed under low pressure (6 s at 345 kPa), washed under high pressure (6 s at 1390 kPa), or not washed. The fruit were transported to the CREC, and stored at 21 ± 1 °C and 93% ± 3% RH, and internal ethylene concentrations were measured 24 h after washing.

Fig. 2. Scanning electron micrographs of the surface of orange fruit that were not washed (**A**) or washed for 10 s under low [345 kPa (**B**)] or high [1380 kPa (**C**) and 2760 kPa (**D**)] pressure.



Results

Effect on morphology. The epicuticular wax fine structure of nonwashed citrus fruit consisted of platelets that covered most of the peel surface (Fig. 2A). Since the platelets did not form a contiguous sheet, regions including stomatal pores were not covered by platelets. The platelets were usually oriented parallel to and closely associated with the peel surface. However, some platelets appeared to be only loosely attached to the surface and extended away from the cuticle. Washing under low pressure (345 kPa) for 10 s had no apparent effect on wax fine structure (Fig. 2B). Washing under high pressure (1380 kPa), however, removed most of the epicuticular wax platelets (Fig. 2C). Washing at 2760 kPa stripped nearly all of the platelets (Fig. 2D). Similar results were observed for white grapefruit (not shown). No cutin matrix damage, such as abrasions, was observed for any treatment.

X-ray analysis for silicon showed that sand grains were found among the wax platelets of nonwashed fruit (Fig. 3 A and B) or fruit washed at low pressure (345 kPa, Fig. 3 C and D), but were nearly absent on fruit washed at high pressure (2760 kPa, Fig. 3 E and F). None of the sand grains observed on the peel of HPW fruit were embedded into the cuticle.

Effect on gas exchange. In the first study on the effect of washing on gas exchange, mass loss of white grapefruit after washing was not affected by washing treatment (no washing, low pressure washing, or HPW) or surfactant pretreatment (average mass loss on a fresh mass basis: 0.65 ± 0.03 and 0.59 ± 0.03 $g \cdot kg^{-1} \cdot h^{-1}$ at 3 and 14 h after washing, respectively). Exchange of water, O_2, or CO_2 at the midsection of the fruit were also not affected by washing treatment or surfactant pretreatment (average water, O_2, and CO_2 exchange: 4.2, 0.90, and 0.033 $mmol \cdot m^{-2} \cdot h^{-1}$, respectively).

In the second study on the effect of washing on gas exchange, washing treatment (no washing, brush only, or low or HPW) did not affect mass loss of white grapefruit or oranges at 3, 6, or 24 h after washing (data not shown). However, average mass loss for white grapefruit and for oranges differed throughout subsequent storage. For example, mass loss at 3 h after washing was 0.56 ± 0.03 and 0.65 ± 0.03 $g \cdot kg^{-1} \cdot h^{-1}$ (fresh mass basis) for white grapefruit and oranges, respectively.

Effect on internal gas composition. In general, HPW of white grapefruit for 10 s did not affect internal gas concentrations (Table 2). Among nonwaxed fruit, HPW for 60 s, however, stimulated an apparent ethylene wound response within 9 h after washing (Fig. 4). Internal ethylene concentrations of nonwaxed white grapefruit increased from near zero concentrations (<0.05 $\mu L \cdot L^{-1}$) before washing to ≈0.15 and 0.31 $\mu L \cdot L^{-1}$ at 18 h after washing at 1380 and 2760 kPa, respectively. Ethylene concentrations returned to near zero concentrations at 45 h after washing. Application of wax after washing caused ethylene to accumulate to even higher concentrations in the fruit regardless of washing treatment (Fig. 4). Internal ethylene concentrations of waxed fruit increased during the initial 3 h after washing (≈2 h after waxing) and attained a near steady-state level thereafter.

Internal O_2 concentrations of nonwaxed fruit were not affected by washing for 60 s and remained near constant throughout storage (Fig. 4). However, wax application caused internal O_2 concentrations to decline rapidly during the initial 18 h after washing and waxing. Near steady-state O_2 concentrations of waxed fruit were attained by the 18 h sampling.

Internal CO_2 concentrations of nonwaxed fruit washed for 60 s at 345, 1380, and 2760 kPa increased ≈10%, 60%, and 95%, respectively, within 18 h after washing. Wax application increased internal CO_2 concentrations to increase rapidly during the initial 18 h after washing and waxing. Near steady-state concentrations were maintained thereafter.

At the 18-h sampling period, ethylene concentrations were highest and O_2 and CO_2 were near steady-state concentrations (Fig. 4). Therefore, this period was used to provide an overall assessment of washing treatment effects. Wax application increased internal ethylene and CO_2 concentrations and decreased O_2 concentrations (Table 2). Analysis of data for only nonwaxed fruit showed that internal ethylene concentrations increased with nozzle pressure or period of exposure.

The effect of nozzle pressure and period of exposure on internal ethylene, O_2, and CO_2 concentrations was examined in more detail for white and red grapefruit, oranges, and tangelos. The relationship between treatment and the stimulation of wound ethylene was inconsistent (Fig. 5). However, internal ethylene concentrations generally remained low (<0.05 $\mu L \cdot L^{-1}$) when exposure time was less than 30 s and nozzle pressures were less than 2070 kPa. Internal ethylene concentrations were consistently higher for red grapefruit and 'Hamlin' oranges (Fig. 5 B and C) than for white grapefruit and tangelos.

The effect of nozzle pressure and period of exposure on internal O_2 and CO_2 concentrations was analyzed by multiple linear regression. As nozzle pressure and period of exposure increased, internal O_2 concentrations decreased for red grapefruit and 'Orlando' tangelos:

Red grapefruit internal O_2 (kPa) = 19.1 – 0.00020 × nozzle pressure (kPa) – 0.0030 × period of exposure (s); $r^2 = 0.29$.

'Orlando' tangelo internal O_2 (kPa) = 20.0 – 0.00056 × nozzle pressure (kPa) – 0.013 × period of exposure (s); $r^2 = 0.68$.

Conversely, internal CO_2 of red grapefruit increased with nozzle pressure and period of exposure:

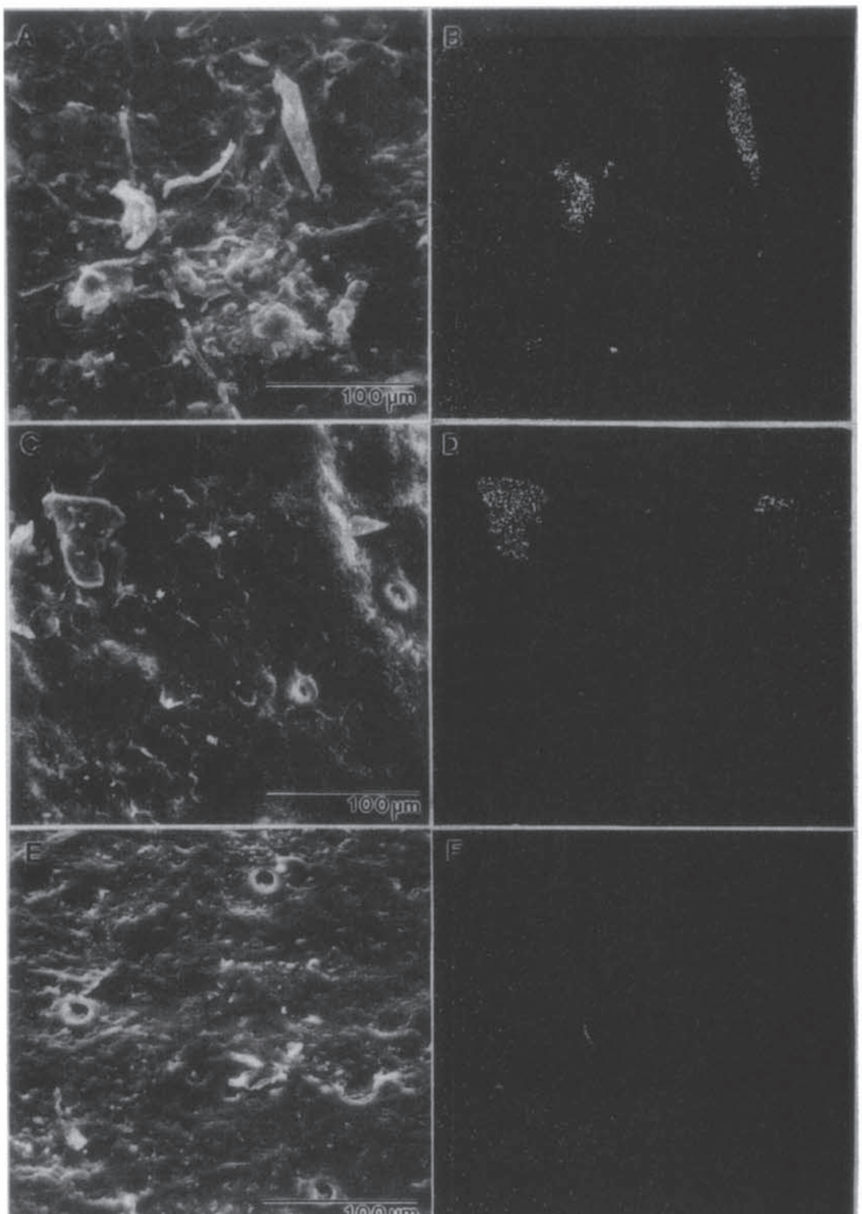


Fig. 3. Scanning electron micrographs (**left column**) and corresponding x-ray maps of silicon (**right column**) of the surface of white grapefruit that were not washed (**A** and **B**) or washed for 10 s under low [345 kPa (**C** and **D**)] or high [2760 kPa (**E** and **F**)] pressure.

Table 2. Effect of nozzle pressure, period of exposure, and wax application on internal gas concentrations of white grapefruit[z].

Nozzle pressure (kPa)	Exposure period (s)	Internal gas level: Ethylene (μL·L^{-1}) Not waxed	Ethylene Waxed	O_2 (kPa) Not waxed	O_2 Waxed	CO_2 (kPa) Not waxed	CO_2 Waxed
345	10	0.04 ± 0.04	0.45 ± 0.16	19.8 ± 0.2	5.0 ± 0.9	1.0 ± 0.2	6.9 ± 0.3
	60	0.03 ± 0.03	0.70 ± 0.21	19.5 ± 0.3	2.7 ± 1.0	1.1 ± 0.4	6.8 ± 0.2
1380	10	0.04 ± 0.02	0.85 ± 0.28	19.6 ± 0.1	3.6 ± 0.7	0.9 ± 0.1	7.0 ± 0.4
	60	0.15 ± 0.04	0.97 ± 0.51	19.7 ± 0.2	5.9 ± 1.1	1.0 ± 0.1	6.3 ± 0.3
2760	10	0.06 ± 0.02	1.12 ± 0.42	19.5 ± 0.1	3.2 ± 1.1	1.2 ± 0.2	7.2 ± 0.4
	60	0.31 ± 0.07	1.20 ± 0.26	19.3 ± 0.2	2.0 ± 0.4	1.5 ± 0.1	8.4 ± 0.6

[z]Shellac-based water wax was applied within 1 h after washing. Fruit were held at 24 °C and 50% relative humidity. Gas samples were taken during a 2-h sampling period beginning 18 h after washing. Values represent means (±SE) of six fruit. The main treatment effect of wax application was significant ($P < 0.01$) for ethylene, O_2, and CO_2 concentrations. The main treatment effect of nozzle pressure was significant ($P < 0.01$) for CO_2 level.

Red grapefruit internal CO_2 (kPa) = 1.1 + 0.00022 × nozzle pressure (kPa) + 0.0017 × period of exposure (s); $r^2 = 0.37$.

Using these models and the parameter extremes (345 kPa, 10 s and 3445 kPa, 120 s), the calculated ranges for internal O_2 are 19.0 to 18.0 kPa and 19.7 to 16.5 kPa for red grapefruit and 'Orlando' tangelos, respectively. The calculated range of internal CO_2 for red grapefruit is 1.1 and 2.0 kPa. The relationship among internal gas level and nozzle pressure and period of exposure was not significant for other varieties.

Red grapefruit washed under low or high pressure in a commercial packinghouse had internal ethylene concentrations of 0.09 ± 0.04 and 0.05 ± 0.02 μL·L^{-1}, respectively. Of 50 fruit washed for each treatment, 23 low-pressure washed fruit and 21 HPW fruit had measurable internal ethylene concentrations (>0.05 μL·L^{-1}). Nonwashed fruit did not have measurable ethylene concentrations.

Discussion

The effects of washing on peel physiology may be classified according to the activating process: 1) peel fracture, 2) cuticle abrasion or epicuticular wax stripping, and 3) stress response stimulation.

First, HPW does not commonly disrupt the peel integrity of sound fruit. Reports of fracturing or tearing caused by HPW have been associated with citrus fruit that are damaged before washing. Rotted or physically damaged fruit rupture during washing due to the lack of peel integrity, the force of high pressure water, and the tearing action of the brushes.

Second, HPW strips away many of the epicuticular wax platelets, but apparently does not abrade the peel surface (Fig. 2 C and D). Despite the removal of wax platelets by HPW, water loss did not increase (Table 2). Previous reports showed that water loss increased after low pressure washing of citrus fruit possibly due to damage to the surface or loss of waxes (Hagenmaier and Baker, 1993; Millier and Brown, 1973). The importance of waxes on citrus fruit water loss is supported by studies in which water loss and total amount of epicuticular wax were inversely correlated (Albrigo, 1972).

Low-pressure washing had no apparent effect on the fine structure of the epicuticular waxes (Fig. 2B). This is corroborated by a previous study in which washing had no effect on total peel wax quantities (Albrigo, 1973). Histological studies, however, indicate that low-pressure washing removes epicuticular waxes (Millier and Brown, 1973).

Although the discrepancies between this and previous studies are not understood, the type of bristles and rotation speeds used to brush the fruit may play an important role in affecting water loss. The rotary brush used in this study was comprised of x-shaped low density polyethylene bristles. These bristles have been recently introduced to reduce damage to the fruit. In previous studies, we also found that washing on a firmer polypropylene brush increases water loss (Petracek, 1995). If the removal of epicuticular wax does not affect gas exchange, enhanced water loss may have resulted from cutin matrix damage. The effect of bristle type and rotation speed on cuticular damage requires further examination.

The primary benefit of HPW is that surface debris such as sand particles (Fig. 3C), scale, and mold spores are removed along with the epicuticular wax platelets. Similarly, the removal of chemical residues such as pesticides and surfactants from the peel surface may also be facilitated by stripping the surface waxes. Under conventional low pressure washing, residue removal may be slow since diffusion-controlled desorption is a relatively slow process. Stripping the fruit surface of cuticular waxes and associated chemical deposits could hasten residue removal by reducing the importance of desorption.

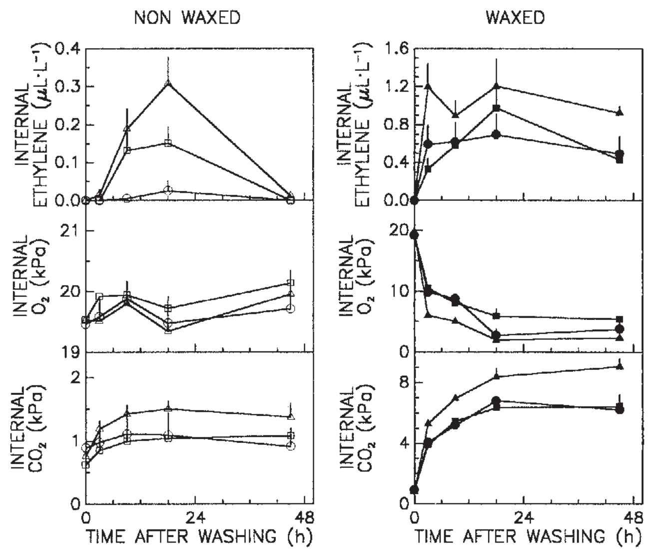


Fig. 4. Effect of high-pressure washing and waxing on internal gas composition of white grapefruit. Nonwaxed fruit were stored at 24 °C and 45% relative humidity (RH) after 60 s exposure to low- (345 kPa ○) or high-pressure (1380 □ or 2760 kPa △) washing. Waxed fruit were stored at 24 °C and 45% RH after 60 s exposure to low pressure (345 kPa ●) or high pressure (1380 ■ or 2760 kPa ▲) washing. Internal ethylene, O_2, and CO_2 concentrations were measured before and 3, 9, 18, and 45 h after washing. Bars represent SE for the means of six fruit.

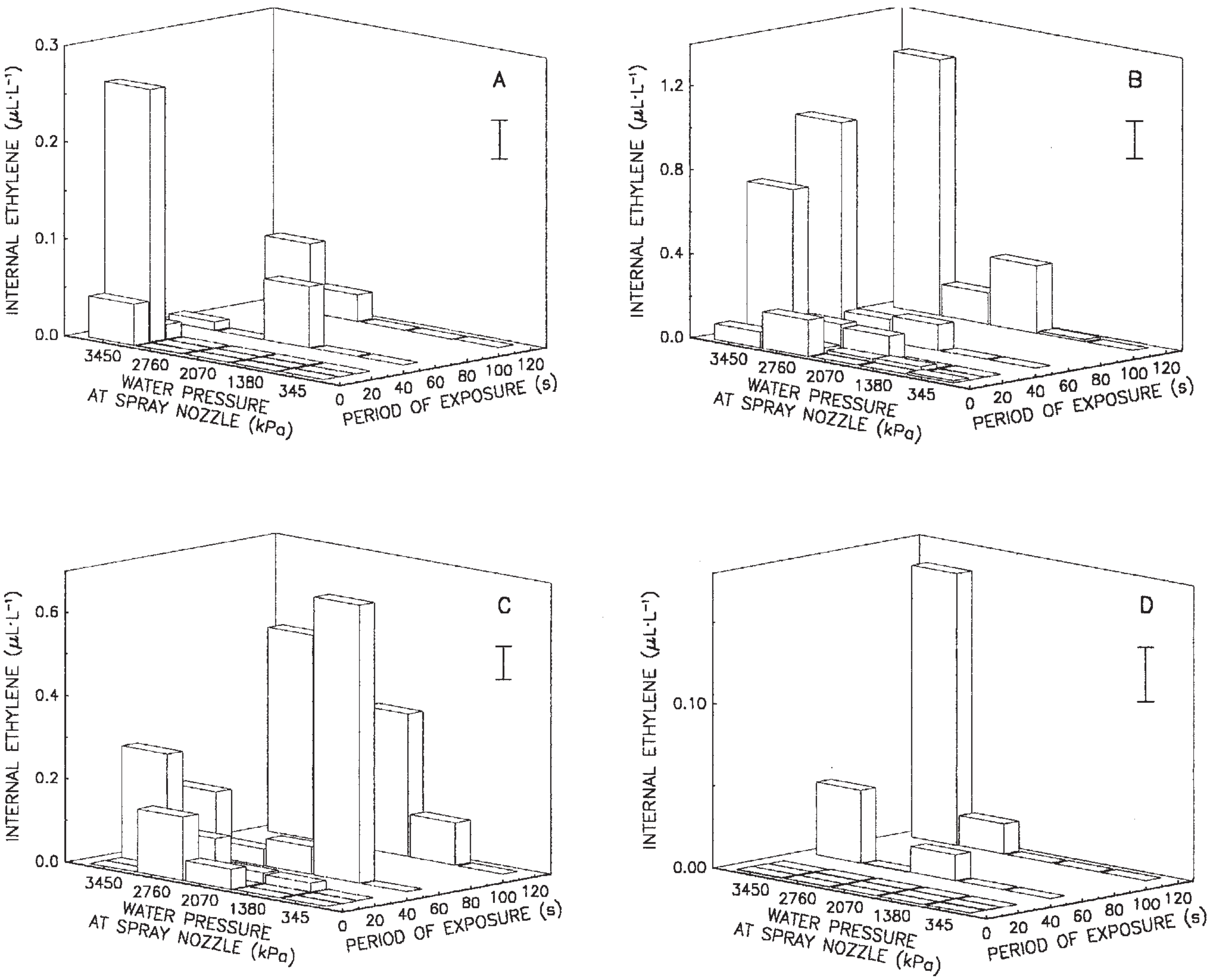


Fig. 5. Effect of nozzle pressure and period of exposure on internal ethylene concentrations. White (**A**) and red (**B**) grapefruit, oranges (**C**), and tangelos (**D**) were washed for 10, 20, 30, 60, or 120 s at 345, 1380, 2070, 2760, or 3450 kPa nozzle pressure. Internal ethylene concentrations (means of five fruit) were measured 24 h after washing. Bars represent LSD ($P = 0.05$).

Third, HPW stimulated an apparent ethylene wound response when fruit were washed under higher pressures and prolonged periods (Table 2, Fig. 5). Vines et al. (1968) demonstrated that dropping citrus fruit produces a similar wound response. The physiological or practical significance of this wound response has not been determined. Informal inspection of the fruit two weeks after washing found no apparent symptoms of damage. Moreover, no peel disorders or signs of visible damage such as discoloration have been attributed to citrus fruit commercially washed with high pressure systems. Fruit washed under high pressure in commercial settings are usually washed under lower pressures (<2760 kPa) and for shorter periods of exposure (<20 s) than those conditions that stimulated ethylene production in this study. The lack of reported peel disorders may result from these milder washing conditions and invariable prompt wax application.

HPW could influence internal O_2 and CO_2 gas concentrations either by stimulating respiration as a wound response and/or by improving peel permeability. Internal O_2 concentrations could be reduced by increased O_2 uptake, but elevated by increased permeation. In contrast, internal CO_2 concentrations could be elevated by increased CO_2 production, but reduced by increased permeation. If gas exchange remains constant (see above), but internal O_2 concentrations decrease (see above) and CO_2 concentrations increase (Table 2, Fig. 4) as they did in some cases, then the influence of HPW on the citrus peel may be attributed to a stimulated wound response rather than changes in permeability. The lack of substantial effect of HPW on internal gas levels suggests that the response may be too small and/or variable to detect by the approaches used in these studies. Other approaches such as a combined analysis of gas exchange, internal gas level, and respiration rates may be better able to detect subtle changes in the peel. Alternatively, since washing may influence only the surface or outermost volume of the fruit, more detailed evaluations of wound response and permeability may be achieved by using isolated peel or cuticle systems rather than the whole fruit.

While the presence of ethylene may indicate some level of peel damage has occurred, the actual level of ethylene in the fruit is low compared with fruit coated with waxes. The waxing process itself, including the use of high temperature driers, may stimulate its own wound response and thus increase ethylene production and respiration. However, waxes are effective barriers to gas permeation (Hagenmaier and Shaw, 1992) and have resulted in a buildup of internal ethylene concentrations (Baldwin et al., 1995). Thus, the effect of waxing on gas exchange, internal concentrations of ethylene, O_2, and CO_2, and subsequently on citrus fruit physiology may trivialize washing effects (Fig. 4, Table 2).

Literature Cited

Albrigo, L.G. 1972. Distribution of stomata and epicuticular wax on oranges as related to stem end rind breakdown and water loss. J. Amer. Soc. Hort. Sci. 97:220–223.

Albrigo, L.G. 1973. Some parameters influencing development of surface on wax citrus fruit. Proc. Intl. Soc. Citricult. 3:107–115.

Amat, S.R. 1988. Defectos y alteraciones de los frutos citricos en su comercializacion. Lit. Nicolau, Almassora, Spain.

Baldwin, E.A., M. Misperos-Carriedo, P.E. Shaw, and J.K. Burns. 1995. Effect of coatings and prolonged storage conditions on fresh orange flavor volatiles, degrees brix, and ascorbic acid levels. J. Agr. Food Chem. 43:1321–1331.

Chace, W.G., P.L. Davis, and J.J. Smoot. 1969. Response of citrus fruit to controlled atmosphere storage. Proc. XII Intl. Congr. Refrigeration III:1–8.

Grierson, W. and W.F. Newhall. 1956. Degreening of citrus fruit. Annu. Rpt. Fla. Agr. Expt. Sta., Univ. Fla., Gainesville. p. 185–188.

Hagenmaier, R.D. and P.E. Shaw. 1992. Gas permeability of fruit coating waxes. J. Amer. Soc. Hort. Sci. 117:105–109.

Hagenmaier, R.D. and R.A. Baker. 1993. Cleaning method affects shrinkage rate of citrus fruit. HortScience 28:824–825.

Kaplan, H.J. 1986. Washing, waxing, and color-adding, p. 379–395. In: W.F. Wardowski, S. Nagy, and W. Grierson (eds.). Fresh citrus fruit. AVI, New York.

Katz, M. 1995. High-pressure washing boosts packout. Citrograph (June):1–3.

Millier, W.F. and G.K. Brown. 1973. Citrus fruit appearance, weight loss, and internal condition inferences for mechanical harvesting. USDA Tech. Bul. ARS-W-5.

Parker, M.L., W.F. Wardowski, and D.H. Dewey. 1984. A damage test for oranges in a commercial packinghouse line. Proc. Fla. State Hort. Soc. 97:136–137.

Petracek, P.D. 1995. A technique for measuring gas exchange through the peel of intact citrus fruit. Proc. Fla. State Hort. Soc. 108:288–290.

Sakiadis, B.C. 1984. Fluid and particle mechanics, p 5-1–5-68. In: R.H. Perry, D.W. Green, and J.O. Maloney (eds.). Perry's chemical engineers' handbook. 6th ed. McGraw-Hill, New York.

Sears, F.W., M.W. Zemansky, and H.D. Young. 1979. University physics. Addison-Wesley Publishing Co., London.

Smoot, J.J., L.G. Houck, and H.B. Johnson. 1971. Market diseases of citrus and other subtropical fruit. USDA Agr. Handbook 398.

Spraying Systems Co. 1989. Spraying systems sales and engineering manual. Wheaton, Ill.

Tidwell, A.N., A.R. Gonzalez, P. Fenn, B.P. Marks, and A. Mauromoustakos. 1997. High pressure washing to remove decayed tissue and improve quality to clingstone peach puree. J. Food Sci. 62:131–134, 148.

Vines, H.M. and M.F. Oberbacher. 1961. Changes in carbon dioxide concentrations within fruit and containers during storage. Proc. Fla. State Hort. Soc. 74:243–247.

Vines, H.M., W. Grierson, and G.J. Edwards. 1968. Respiration, internal atmosphere, and ethylene evolution of citrus fruit. Proc. Amer. Soc. Hort. Sci. 92:227–234.