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Effect of high-pressure hot-water washing treatment on fruit quality, insects, and disease in apples and pears Part I. System description and the effect on fruit quality of 'd'Anjou' pears

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Abstract

A manually operated high-pressure hot-water washing system consisting of a boiler, hot-water mixing tank, contact loop, heat exchanger, spray mixing tank, high-pressure hot-water washing manifold, low-pressure fresh water rinse manifold, and pressure pump was constructed and installed in a packingline. The system developed 20–50 °C washing water at pressures up to 980 kPa. 'd'Anjou' pears (*Pyrus communis* L.), shortly after harvest, and after storage for 3 and 4 months in regular air (RA) or for 4, 7 and 8 months in controlled atmosphere (CA) at −1 °C were washed through the packingline with different wetting agents (0.1% Silwet, 0.01 and 0.1% Defoamer, and water), water pressures (regular and high-pressure (210–980 kPa)), water temperatures (control (tap water, 4–22 °C), 40 °C, and 50 °C), and brushes (soft and firm), respectively. The effect of the washing conditions on fruit quality was investigated after 1 month of storage at −1 °C to simulate shipping condition, and then again after 1 week at 20 °C to simulate marketing condition. Hot-water caused severe heat scald. When nozzle temperature was 50 °C, the incidence of heat scald increased to over 50% for the fruit stored in RA for 3 months. Combined with hot-water, 540 kPa high-pressure washing increased the incidence of friction discoloration. There were lower incidences of friction discoloration and heat scald for fruit stored in CA for 7 months, in comparison to that in RA for 3 months. However, those fruit did not ripen properly as indicated by a high extractable juice content. Fruit washed at harvest had minor incidences of friction discoloration regardless of different brushes, water pressures, and wetting agents. Fruit washed after storages in either 4 months RA or 4 or 8 months CA suffered a high incidence of friction discoloration including scuffing symptoms and pressure marking. The firm brushes caused a higher incidence of friction discoloration mainly because of scuffing symptoms. However, no differences were found between different water pressures and wetting agents with respect to friction discoloration. Fruit stored for 4 months RA suffered 26–28% friction discoloration in comparison to 16–18% in CA stored fruit with firm brush washing. Extended CA storage increased friction discoloration even with soft brush washing. The results suggest that a washing system with high-pressure spray, <30 °C warm water, wetting agent Defoamer and rotating soft brushes were significantly effective in removing surface pests and decay control without causing internal or external damage of fruit.
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1. Introduction

The presence of surface arthropods (spider mites, mealy bugs, scale, and lepidopteran and mite eggs) on apples and

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pears has been a concern for many export markets (Whiting et al., 1970). As insects have developed resistance to control chemicals and consumers desire less chemicals on their produce, it would be desirable to develop a non-chemical method to remove pests.

Postharvest heat treatments, including hot air, vapor heat, dips, sprays, and hot-water brushing, have been shown to remove and/or control insects and diseases in fruit and vegetables (Fallik et al., 1999, 2000; Karabulut et al., 2002; Lichter et al., 2000; Lurie, 1998; Porat et al., 2000a,b; Prusky et al., 1999). However, not all hot-water treatments have been successful. Peaches subjected to hot-water (55 °C) for 90–300 s were more susceptible to brown rot (*Molinia fructicola*) infection during storage (Phillips and Harris, 1979; Smith and Anderson, 1975; Smith and Redit, 1968).

Commercial pear packing operations in the Pacific Northwest have generally use cold-water wash/rinse systems operating in a water pressure of 200–300 kPa. A number of packing houses are using high-pressure recirculated cold-water washing to clean apples and pears. The practice is becoming more popular as the use of Surround® (Kayolin clay) increases. While the systems have been effective in removing and killing eggs of codling moth and European red mite, and removing San Jose scale and grape mealybug, the incidence of storage decay has increased dramatically (Peter Sanderson, personnel communication). Preliminary experiments demonstrated that washing pressures of ≥1400 kPa or spray temperatures ≥55 °C seriously damaged pear fruit. As temperature of ≥60 °C is necessary to control organisms and water of this temperature cannot be directly applied to pears, it is evident that a heated contact loop and heat exchanger must exist in the system to control the spread of decay fungi.

Combinations of hot-water, high-pressure water, wetting agents, and varied brush washing were proposed to eliminate pests on the fruit surface during packing process. It is essential that the proposed procedure does not cause internal or external damage of fruits. Hot-water or hot air caused abnormal softening in mango and papaya (Jacobi and Wong, 1992; Paull, 1995), as well as flesh darkening on nectarines (Lay-Yee and Rose, 1994). Pear fruit ‘friction discoloration’ is defined as a skin browning that occurs after damage of epidermal cells of pear fruit from mechanical friction during packing (Wang and Mellenthin, 1973). Friction discoloration is also referred to as “brush or belt burning” and “scuffing” of the fruit surface. Phenolic compounds that leak from the injured epidermal cells are enzymatically oxidized to form unstable quinone compounds, which further react with amino acids and proteins to form complex brown polymers and thus discolor the fruit surface (Walker, 1977; Wang and Mellenthin, 1973, 1974). Another surface disorder occurring frequently during packing is heat scald. When pears pass through the heat tunnel, fruit surface color changed to dark brown or black. Heat scald is a cosmetic symptom with only a few layers of cells immediately beneath the epidermis affected.

The purpose of this project was to determine the effect of a high-pressure hot-water system on fruit quality, insects, and disease in apples and pears. The project consisted of four sections. This section describes the system used and discusses the effect of the system on fruit quality; Section 2 (Spotts et al., 2006) discussed the effect of the system on fruit decay and spore buildup within the system; Section 3 (Hansen et al., 2006) discussed the removal of surface pests; and Section 4 (Neven et al., 2006) discussed the effect of the system on removing surface arthropod eggs.

2. Materials and methods

2.1. High-pressure hot-water (HPHW) washing system

HPHW washing system was designed by Heath Rush (Rush & Associates, Wenatchee, WA). The system consisted of a boiler, hot-water mixing tank, contact loop, heat exchanger, spray mixing tank, high-pressure hot-water washing manifold, low-pressure fresh water (LPFW) rinse manifold, pressure pump, and associated valves and piping. Total system capacity was 700 L.

A Raytherm type WH-182 boiler (Raypak, Inc., Oxnard, CA) heated water to ≥60 °C in the hot-water mixing tank (302 L). A Honeywell type L6006C Aquastat (Honeywell, Minneapolis, MN) attached to the outside of the mixing tank controlled the boiler. The Aquastat had a range of 15 to 93 ± 1 °C when adjusted to its lowest differential. Hot-water passed through the contact loop and heat exchanger or directly to the spray tank. The contact loop was constructed of 16.6 m × 76.2 mm chlorinated polyvinyl chloride (CPVC) so as to contain 75.7 L of water, and was insulated with 50 mm of styrofoam to reduce heat loss. Water from the contact loop was directed through the heat exchanger or directly to the spray tank. The SR2 MSG-12 plate heat exchanger (APV Systems, Goldsboro, NC), equipped with 61 plates, and had a heat transfer area of 10.15 m^2. In the spray tank (227 L) hot-water from the heat exchanger and/or hot-water tank, the HPHW washing spray manifold, and the LPFW rinse manifold was mixed. A Baldor 1NN3314T 15 hp centrifugal pump (Baldor Electric Co., Fort Smith, AR) pressurized the spray tank water and directed it to the HPHW manifold or back to the heat exchanger and/or hot-water mixing tank. The HPHW washer manifold consisted of 15, QPTA 40° nozzles (Spraying Systems, Co., Wheaton, IL), arranged in six rows mounted 300 mm above the washer brush bed. Two, QPTA 95° nozzles mounted 300 mm above the 2-brush LPFW rinse bed were adjusted to provide fresh water at the rate of 0.132 L s^{-1}. The temperature of the LPFW rinse ranged from 3 to 25 °C depending on the time of the year. As the LPFW manifold continued to add water to the system, water excess to the system's capacity was diverted out the spray tank overflow. The LPFW manifold provided a quantity of water equivalent to the capacity of the system every 5544 s. Valves located within the system permitted flow rates be adjusted in the contact loop and spray water temperatures from 25 to 60 °C, at pressures from 70 to 980 kPa at the HPHW manifold.

System flow rates were measured with Omega FP6501 flow meters, with an accuracy of 0.1 °C, and temperatures measured with Omega military tank-therm thermocouples (Omega Engineering Inc., Stamford, CT), with an accuracy of 0.1 °C, at various places throughout the system. Readings were collected every second, averaged over a 7 s period, and logged to a computer data file via a Windows based program.

For the system operation, approximately 3600 s was required to bring the contact loop up to operating temperature. Temperature stability at the HPHW spray manifold was ±0.3 °C at the set spray nozzle for a period of 3600 s. Water exiting the heating tank and in the contact loop were held within 65.0 ± 1.3 and 63.5 ± 1.3 °C, respectively. The cyclical fluctuation in temperature was due to the Honeywell type L6006C Aquastat, which measured the surface temperature of the insulated hot-water mixing. Temperature stability could have been significantly improved by controlling the boiler with a thermocouple type thermostat and/or a variable heat-input boiler.

System stabilization was achieved within 600 s when the pressure of the HPHW spray manifold was reset. As the pressure was increased, the amount of water discharged through the HPHW spray manifold increased. As the flow rates through the contact loop and hot-water mixing tank were maintained at 1.262 ± 0.003 L s^{-1}, the percentage of the water that was sent back to the hot-water mixing tank decreased from 52.6% at 140 kPa to 33.9% at 840 kPa. However, as most of the experiments were run at 420 or 560 kPa, the percentage of water reheated varied by approximated 5%.

2.2. Packingline

The Mid-Colombia Agricultural Research and Extension Center packingline consisted of a vertical emersion dump tank, 1.5 m elevator with fresh water rinse, soap applicator, 12 washing brushes, 8 HPHW washing brushes, 2 LPFW rinsing brushes, 11 drying and/or waxing brushes, 3.6 m hot-air drying tunnel, and 2.4 m sorting belt. The width of the system was 300 mm. Fruit capacity, adjustable from 83 to 500 g s^{-1}, was set at 375 g s^{-1}.

The vertical emersion dump tank (4350 L) contained 182 kg of sodium silicate as a flotation salt necessary to float pear fruit (density = 1.08 kg L^{-1}). The fresh water rinse on the elevator was 50 mL s^{-1} applied through 2 TeeJet 8004 nozzles (Spraying Systems, Wheaton, IL) mounted 300 mm above the elevator. The fresh water temperature ranged from 3 to 25 °C depending on the time of year. Acidex fruit wash soap (Pace International, Seattle, WA), diluted 150 mL to 25 L water, was applied at the first brush of the 12-brush wash bed, by a peristaltic pump at the rate of 0.694 mL s^{-1}. The fruit passed over an 8-brush HPHW and 2-brush LPFW bed after washing. The fruit spent 40 ± 2, 26 ± 2, and 6.5 ± 1 s, respectively, on the washing, HPHW, and LPFW brushes, respectively. The 8-brush HPHW wash/rinse bed served as an additional soap washing bed when the HPHW manifold was not used (i.e. control fruit). The 2-brush LPFW manifold served as the final rinse for the fruit, and was the only rinse used for the control fruit. The washing and/or rinsing brushes were 124 mm in diameter; with either 0.38 mm (hard) or 0.30 mm (soft) cross-linked polyethylene (PEX) bristles (American Brush Co., Portland, OR) and rotated at 0.5 s^{-1}. The drying/waxing brushes were covered with a polyethylene coated nylon belt for these experiments. The forced air-drying tunnel was set at 38 °C. Airflow was 560 L s^{-1}.

The desired temperature and pressure regime was stabilized with a continual stream of fruit coming from the dump tank. Experimental lots of fruit were hand placed onto the elevator into the stream of fruit coming from the dump tank. Fruit for the postharvest evaluations was collected from the sorting belt and placed into wooden boxes with polyethylene liners. Fruit for pathological and insect studies was removed from the line prior to the drying tunnel.

2.3. Harvest and storage of fruit

'd'Anjou' pears were harvested at commercial maturity with flesh firmness under 62 N (Hansen and Mellenthin, 1979) in 2001 and 2003 from the Oregon State University, Mid-Colombia Agricultural Research and Extension Center Orchard. Fruit in commercial bins (450 kg) were stored in commercial regular air (RA) or controlled atmosphere (CA, 2 kPa oxygen + 1 kPa carbon dioxide) at −1 °C. Fruit were run through the experimental packingline under different conditions shortly after harvest (16 days in RA at −1 °C after harvest), after 3 or 4 month RA storage, or 4, 7, or 8 month CA storage, and the effect of washing conditions on fruit quality was evaluated.

2.4. Fruit treatment

Three boxes (20 kg, about 80 fruit per box, representing the three replicates) of fruit randomly selected from five bins were dipped in one of four wetting agent treatments (water only, 0.1% Silwet (Helena Chemical Co., Memphis, TN), and 0.01% and 0.1% silicone Defoamer with polydimethly siloxane emulsion (Defoamer, Ivanhoe Industries Inc., Mundelein, IL)) for 60 s. The fruit were hand loaded onto the elevator from the dump tank and rinsed, washed, rinsed, and dried as previously described. High-pressure washing treatment included none, 210, 420, 560, 700, 840, and 980 kPa water sprayer pressures (the "none" pressure control was rinsed by the low-pressure fresh water wash manifold only). Water temperature treatments included 40 °C, 50 °C, and tap water as control, which seasonally ranged from 4 to 22 °C. Brush treatments included soft (0.30 mm PEX) and firm (0.38 mm PEX). Different combinations of the four factors (Table 1) were designed for different storage durations, for eliminating unpromising treatments or adding important

Table 1
Treatment combinations for five different experiments in 2001 and 2003

Treatment factor	Experiment (year, storage condition and duration)				
	2001 RA 3 months	2001 CA 7 months	2003 at harvest	2003 RA and CA 4 months	2003 CA 8 months
Water temperature (°C)	40	40	(15)	(8)	(22)
	50 (4)[a]	50 (21)			
Wetting agent	None	None	Water only Silwet 0.1%	Water only Defoamer 0.1%	Water only Defoamer 0.1%
			Defoamer 0.01%	Defoamer 0.01%	Defoamer 0.01%
Water pressure (kPa)	210	210	None	None	None
	560	560	420	420	420 560 700 840 980
Brush	Soft	Soft	Firm Soft	Firm Soft	Soft
Number of treatment combination	2 × 1 × 2 × 1 + 1 (control) = 5	2 × 1 × 2 × 1 + 1 (control) = 5	1 × 3 × 2 × 2 = 12	1 × 3 × 2 × 2 = 12	1 × 3 × 6 × 1 = 18

[a] Temperatures in parentheses indicate the tap water temperature used on the day.

factors for later experiments based on the results in earlier experiments.

Washed and dried fruit were packed into 20 kg wooden boxes (one per replicate) with perforated polyethylene liners and stored in RA at −1 °C for 30 days to simulate a period of handling and shipping. Then fruit were removed from cold storage and held at 20 °C for 1 and 7 days before the assessment of quality parameters to simulate marketing conditions.

2.5. Fruit quality evaluation

Friction discoloration and heat scald of fruit surface were visually assessed after handling and shipping for 30 days at −1 °C. Fruit with ≥6 disorder spots or ≥300 mm^2 disorder area in the entire surface were considered as culls. Incidences of friction discoloration and heat scald were recorded separately and expressed as percent of fruit with the symptoms, respectively.

Flesh firmness, extractable juice, titratable acidity, and soluble solids were determined on day 1 and 7 of ripening using 10 fruit from each replicate (box). Flesh firmness was measured using a fruit texture analyzer (Model GS-14, Guss Manufacturing Ltd., Strand, South Africa) with an 8 mm plunger that penetrates 9 mm in 0.9 s. Two measurements were obtained per fruit from opposite sides of the equator region where 20 mm-diameter peel discs were removed.

Extractable juice was obtained from 100 g flesh tissue (peel and core removed). A juicer (Model 6001, Acme Juicer Mfg Co., Sierra Madre, CA) was used with a milk filter (Schwartz Manufacturing Co., Two Rivers, WI) at about 2500–3000 × *g* for 60 s. Juice amount was measured in a 100 mL graduated cylinder (Chen et al., 1981) and expressed on a fresh weight basis.

Soluble solids content and titratable acidity were measured using the juice extracted above. Soluble solids content was measured by a refractometer (Model N1, Atago, Tokyo, Japan). Titratable acidity was determined by titrating a mixture of 10 mL juice and 40 mL ion-free water with 0.1 N NaOH to pH 7.2 using a titration system (Model T80/20, Schott-Gerate, Hofheim a. Ts., Germany) and expressed as concentration of H^+, mmol L^{-1} (Chen et al., 1981).

2.6. Statistical analysis

A split-plot analysis of variance (ANOVA) was used for statistical analysis to determine the effect of brush, washing pressure, and wetting agent on flesh firmness, extractable juice, soluble solids, titratable acidity, and friction discoloration where brush was considered as the main plot; washing pressure as the sub-plot and wetting agent the sub-sub-plot. MINITAB™ Statistical Software (Minitab Inc., State College, PA) was used for the analyses.

3. Results and discussion

3.1. Heat scald and friction discoloration

'd'Anjou' pears run through the packingline with hot-water caused severe heat scald and friction discoloration (Table 2). In comparison with 7-month CA fruit, the fruit stored in RA for 3 months suffered a higher incidence of the disorders (Table 2). Combined with hot-water, 560 kPa high-pressure washing aggravated the disorders significantly (Table 2). Both heat scald and friction discoloration are caused by oxidation of phenolic compounds, which leak from the injured epidermal cells (Walker, 1977). Amiot et al. (1995) noted that total phenolic content in pear peel increased during storage in both CA and RA, however, the increase rate was lower in CA than that in RA.

Heat exposure severity moderates the thermo tolerance response of a commodity, and is dependent on exposure temperature (Lurie, 1998). When pear cells were exposed to 39 °C, which initiated the synthesis of heat shock proteins, heat tolerance was induced in the pear cells. At 42 °C or higher, the synthesis of heat shock proteins was attenuated and pear cells were more likely to suffer heat damage (Ferguson et al., 1994).

Because 40 and 50 °C HPHW treatments caused such severe internal disorders and poor external quality, and as it is likely that the hot-water was the major reason, we eliminated the 40 and 50 °C water HPHW treatments in later experiments (Table 1). However, 30 °C water did not cause heat injury (Spotts et al., 2006); suggesting that is the proper water temperature which effectively removes pests and controls disease without causing disorder.

Fruit treated shortly after harvest suffered slight incidences of friction discoloration (between 1.6 and 6.9%); however, there were no differences among different brushes, water pressures, and wetting agents (Table 3). This suggests that any combination of high-pressure washing system (none or 420 kPa) with different brushes (soft or firm), and wetting agents (water only, or 0.1% Silwet, or 0.1% Defoamer) could be selected for removing surface pests without causing fruit quality damage.

For the experiment using fruit stored for 4 months of RA and CA, we used Defoamer only, because Silwet was registered for preharvest use only, not for postharvest applications. We substituted 0.1% Defoamer for the 0.1% Silwet treatment. After 4 months of RA storage, fruit ran through the line with firm brushes suffered a higher incidence of friction discoloration (>20% affected fruit) than those run through with soft brushes (<8% affected fruit) (Table 3). After 4 months of CA storage, fruit that were run through with firm brushes also suffered a higher incidence of friction discoloration (>16% affected fruit) compared to fruit run through with soft brushes (<7% affected fruit) (Table 3). These results indicate that 'd'Anjou' pears stored in either RA or CA for 4 months were very susceptible to friction discoloration disorders including scuffing and bruising damage, especially when firm brushes were used on the packingline. The increased susceptibility of 'd'Anjou' pears to friction discoloration after a prolonged RA or CA storage might be due to the accumulation of phenolic compounds, especially chlorogenic acid, in the epidermal cells, combined with a structural change of the cuticle layer on the fruit surface (Wang and Mellenthin, 1973, 1974). Therefore, possible mechanical friction on the packingline should be eliminated to avoid any damage to epidermal cells.

'Pressure burn' was found in all treatments after the fruit had been run through the packingline and the damage was more severe when firm brushes were used (data not shown).

Pressure burn generally developed on the fruit with 'pressure marks', which were caused by the fruit making contact with the bottom or sides of the storage bin. During storage, the fruit at bottom or sides of bin suffered partial dehydration and/or the weight from the fruit on the top of them, caused partial flattening at the points of contact. When fruit with 'pressure marks' ran through the packingline, friction caused the marks to turn brown and become unmarketable.

Treatment following 8 months CA storage did not include the firm brushes because of the severe friction discoloration problem. We also increased water pressure from 420 to 980 kPa to determine the effect on insect removal and fruit discoloration. Neither pressures up to 980 kPa or Defoamer caused significant friction discoloration

Table 2
Effect of water pressure and temperature on incidences of heat scald and friction discoloration of 'd'Anjou' pears, which were washed through a packingline

Temperature (°C)	Pressure (kPa)	Incidence of disorder (%)	
		Storage condition	
		RA for 3 months	CA for 7 months
Heat scald			
4–21[a]	None	0 b	0 b
40	210	10 b	2 b
	560	54 a	9 b
50	210	27 b	3 b
	560	70 a	24 a
Friction discoloration			
4–21	None	24 b[b]	17 b
40	210	37 b	11 b
	560	53 a	15 b
50	210	45 ab	16 b
	560	55 a	36 a

Fruit stored at −1 °C in regular air (RA) for 3 months or in controlled atmosphere (CA) for 7 months were used. Washed fruit were stored in RA at −1 °C again for 30 days to simulate a period of handling and shipping, and then were transferred to 20 °C for 1 day before the assessment.

[a] Tap water with 5 °C for the fruit stored in RA for 3 months, and 15 °C for the fruit stored in CA for 7 months.

[b] Mean values within a same column ($n = 3$) for the same category followed by the same letter (a and b) are not significantly different ($P < 0.05$).

Table 3
Effect of brushes, water pressures, and wetting agents on friction discoloration of 'd'Anjou' pears, which were run through a packingline

Brush	Pressure (kPa)	Chemical	Incidence of friction discoloration (%)		
			Experiment (storage condition)		
			At harvest	RA for 4 months	CA for 4 months
Soft	None	H_2O	3.3	5.5	6.2
		Silwet 0.1	5.5	–	–
		Defoamer 0.01	6.9	6.2	6.5
		Defoamer 0.1	–	10.3	7.8
	420	H_2O	3.7	7.0	5.4
		Silwet 0.1	3.4	–	–
		Defoamer 0.01	1.6	6.8	6.3
		Defoamer 0.1	–	9.2	7.1
Means			4.1	7.5	6.6
Firm	None	H_2O	5.2	27.0	16.2
		Silwet 0.1	4.6	–	–
		Defoamer 0.01	5.1	26.8	16.9
		Defoamer 0.1	–	26.8	17.9
	420	H_2O	4.0	28.0	16.5
		Silwet 0.1	5.0	–	–
		Defoamer 0.01	3.9	27.6	16.4
		Defoamer 0.1	–	27.4	16.5
Means			4.6	27.3	16.7
Overall LSD (0.05)			2.8	5.4	4.3
ANOVA (*P* values)					
Brush (B)			0.19^{NS}	0.00^{***}	0.00^{***}
Pressure (P)			0.28^{NS}	0.64^{NS}	0.69^{NS}
Chemical (C)			0.64^{NS}	0.48^{NS}	0.75^{NS}
B × P			0.76^{NS}	0.83^{NS}	0.99^{NS}
B × C			0.78^{NS}	0.38^{NS}	0.98^{NS}
P × C			0.25^{NS}	0.88^{NS}	0.97^{NS}
B × P × C			0.10^{NS}	0.92^{NS}	0.97^{NS}

Fruit shortly after harvest and after 4 months storage at −1 °C in regular air (RA) or controlled atmosphere (CA) were used. Treated fruit were stored in RA at −1 °C again for 30 days to simulate a period of handling and shipping, and then were transferred to 20 °C for 1 day before the assessment. $^{***}P < 0.001$. NS, not significant.

(Table 4). However, there were slightly higher incidences of friction discoloration in the fruit stored for 8 months in CA in comparison with the fruit stored for 4 months (Tables 3 and 4). These results suggest that fruit with 'pressure marks', had an increased accumulation of phenolic compounds in the epidermal cells, and that coupled with the longer storage made the fruit more susceptible to friction discoloration.

3.2. Internal fruit quality

The 40 and 50 °C HPHW treatments did not affect normal ripening of the fruit stored in RA for 3 months (Table 5). However, for fruit stored in CA for 7 months, the 40 and 50 °C HPHW treatment partially inhibited the normal ripening process as indicated by increase in extractable juice content (to about 650 mL kg^{-1}) after 7 days ripening at 20 °C (Table 5). The proper ripeness of 'd'Anjou' pears was defined when flesh firmness decreased to <27 N and extractable juice reduced to <650 mL kg^{-1}. When fruit softened with

Table 4
Effect of different water pressures and wetting agents (chemicals) on friction discoloration of 'd'Anjou' pears, which were washed through a packingline

Pressure (kPa)	Incidence of disorder (%)			Means
	Chemical			
	H_2O	0.01% Defoamer	0.1% Defoamer	
None	7.6	11.2	8.3	9.0
420	8.6	8.4	9.6	8.9
560	10.8	7.9	9.9	9.5
700	7.9	6.6	12.3	8.9
840	11.6	9.1	6.8	9.2
960	7.9	9.8	7.8	8.5
Means	9.1	8.8	9.1	9.0
ANOVA				
Pressure (P)		0.92^{NS}		
Chemical (C)		0.94^{NS}		
P × C		0.92^{NS}		

Fruit stored at −1 °C in controlled atmosphere (CA) for 8 months were used. Washed fruit were stored in RA at −1 °C again for 30 days to simulate a period of handling and shipping, and then were transferred to 20 °C for 1 day before the assessment. NS, not significant.

Table 5
Effect of water pressure and temperature on quality attributes of 'd'Anjou' pears which were washed through a packingline

Temperature (°C)	Pressure (kPa)	Storage condition	
		RA for 3 months	CA for 7 months
Flesh firmness (*N*)			
4–21[a]	None	9.3 a[b]	16.0 b
40	210	11.1 a	17.9 ab
	560	10.2 a	17.9 ab
50	210	12.5 a	17.9 ab
	560	11.6 a	19.8 a
Extractable juice (mL kg^{-1})			
4–21	None	601 a	609 b
40	210	611 a	650 a
	560	619 a	645 a
50	210	621 a	641 a
	560	619 a	653 a
Soluble solids (%)			
4–21	None	13.8 a	13.6 a
40	210	14.1 a	13.0 a
	560	13.5 a	12.8 a
50	210	13.9 a	13.4 a
	560	13.8 a	13.0 a
Titratable acidity (H^+ concentration, mmol L^{-1})			
4–21	None	44 a	37 a
40	210	43 a	36 a
	560	41 a	40 a
50	210	44 a	41 a
	560	44 a	41 a

Fruit stored at −1 °C in regular air (RA) for 3 months or in controlled atmosphere (CA) for 7 months were used. Washed fruit were stored in RA at −1 °C again for 30 days to simulate a period of handling and shipping, and then were transferred to 20 °C for 7 days to simulate marketing condition.

[a] Tap water with 5 °C for the fruit stored in RA for 3 months, and 15 °C for the fruit stored in CA for 7 months.

[b] Mean values ($n = 3$) for the same category followed by the same letter (a and b) are not significantly different ($P < 0.05$).

a less buttery and juicy texture, they tended to have higher extractable juice content. Reduction of extractable juice content is due to an increase of water-soluble pectin in the ripened pear pulp, which increases the hygroscopic binding capacity (Chen and Borgic, 1985).

Different brushes, water pressures, and wetting agents did not cause reduction of internal quality or unusual ripening as reflected by flesh firmness and extractable juice for all at-harvest-fruit and stored fruit (Table 6). Fruit softened normally to below 20 N with a concomitant reduction in extractable juice to 570–640 mL kg^{-1} on day 7 of ripening at 20 °C, depending on storage duration (Table 6). Therefore, the increase of extractable juice in ripened fruit after extended storages indicated that the fruit had a less juicy, and poorer buttery texture (Chen et al., 1981).

Titratable acidity in fruit decreased during storage and decreased faster in fruit stored in RA than in CA (Table 6). Soluble solids content decreased slightly during storage, although a significant increase was found during subsequent ripening regardless of storage time (data not shown).

The results showed that 'd'Anjou' pears were very sensitive to heat and friction. The former caused heat scald and/or ripening disorder and the later caused belt burn and scuffing. On the other hand, apples are generally not as sensitive as pears to the packing process. Apple fruit possess coriaceous peel covered by a thick natural wax. Therefore, apples have less friction disorder. Apples also showed heat resistance to at least 38 °C (Lurie, 1998). A treatment of 38 °C for 4 days significantly decreased ethylene production, softening and deterioration of 'Gala' apples without disorder (Bai et al., 2004). Hot temperature can cause the loss of fruit ripening capacity; however, apples are consumed without ripening. Thus, apples are resistant to packing process in comparison to pears. We did not show the data of quality change of apples caused by the packingline in this manuscript, however, Section 3 (Hansen et al., 2006) and Section 4 (Neven et al., 2006) of this research set showed that hot-water, firm brushes, wetting agents, and high water

Table 6
Effect of washing condition on quality attributes of 'd'Anjou' pears which were washed through a packingline

Attribute	Treatment	Storage condition and duration			
		At harvest	4 months RA	4 months CA	8 months CA
Flesh firmness (*N*)	Control[a]	18.6 ± 2.3	15.4 ± 1.8	10.5 ± 2.5	8.1 ± 4.6
	Treatments	19.2 ± 1.1	15.2 ± 1.1	10.5 ± 0.9	8.3 ± 1.6
Extractable juice (mL kg^{-1})	Control	572 ± 23	623 ± 34	588 ± 17	626 ± 13
	Treatments	581 ± 8	628 ± 14	592 ± 07	631 ± 10
Soluble solids (%)	Control	13.2 ± 0.8	13.2 ± 1.4	13.1 ± 1.1	12.8 ± 1.6
	Treatments	13.2 ± 0.4	13.1 ± 2.0	13.1 ± 0.1	12.6 ± 1.0
Titratable acidity (H^+ concentration, mmol L^{-1})	Control	44 ± 2	31 ± 2	37 ± 6	32 ± 3
	Treatments	45 ± 2	31 ± 1	37 ± 2	33 ± 2

Fruit shortly after harvest, after 4 months storage at −1 °C in regular air (RA) or after 4 and 8 months in controlled atmosphere (CA) were used. Washed fruit were stored in RA at −1 °C again for 30 days to simulate a period of handling and shipping, and then were transferred to 20 °C for 7 days to simulate marketing condition.

[a] Control: washing condition = soft brush + no wetting agent (water) + regular water pressure; treatments: average of all of other washing conditions except heated water and the controls. No significant difference has been found between control and treatments in any attribute at any storage stage with *t* test at $P < 0.05$.

pressure did not cause internal or external disorder of apple fruit.

4. Conclusions

When ‘d’Anjou’ pears had been washed through a packingline shortly after harvest, treatments with different wetting agents, water pressures, and brushes did not cause any substantial increase in friction discoloration. However, fruit stored in either RA or CA for 4 months were susceptible to friction discoloration, including scuffing and bruising injury especially when firm brushes were used in the packingline. A portion of fruit suffered pressure marks, which developed from the partial dehydration of fruit and weight of fruit pressing on each other and the sides and bottom of the bins. When those fruit were run through the packingline, the pressure marks turned brown as a result of friction. Extended storage increased this symptom. The 40 and 50 °C HPHW washing caused severe heat scald and disrupted the normal ripening of fruit as indicated as higher extractable juice.

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