TECHNICAL NOTE:

DEVELOPMENT OF INFRARED RADIATION HEATING METHOD FOR SUSTAINABLE TOMATO PEELING

Z. Pan, X. Li, G. Bingol, T. H. McHugh, G. G. Atungulu

ABSTRACT. *Although lye peeling is the widely industrialized method for producing high quality peeled fruit and vegetable products, the peeling method has resulted in negative impacts by significantly exerting both environmental and economic pressure on the tomato processing industry due to its associated salinity issues and wastewater disposal problems. The objective of this research was to develop alternative peeling methods with reduced or no caustic usage to produce high quality peeled tomatoes. The feasibility of using infrared radiation (IR) peeling and lye-IR peeling as alternative technologies was evaluated against control treatment which used regular lye peeling alone. Peeling performance and peeled tomato quality of three tomato cultivars were determined. The metrics for peeling performance were peelability, peeling easiness, and peeling weight loss. The color and texture of peeled tomatoes were measured as quality indicators. The study showed that IR peeling resulted in a similar peeling easiness but yielded lower peeling loss and firmer peeled product for the same or slightly longer peeling time when compared to regular lye peeling method. Pretreatment with low concentration of lye solution prior to IR treatment did not show any advantages over IR peeling alone. Because IR dry-peeling produced high quality product without using water and salts, it is concluded that it has a good potential as an alternative peeling method to the regular lye peeling method.*

Keywords. *Peeling, Infrared Radiation, Tomato, Lye Peeling, Environment.*

The development of non-chemical dry-peeling technology has recently been identified as a top priority in California for an environmentally friendly tomato processing industry. At present, hot lye peeling and steam peeling are the two commercial techniques adopted by the fruit and vegetable processing industry. Although hot lye (wet-caustic) peeling method is widely used in tomato peeling for producing high quality product with high peelability, the tomato processors are under great pressure to reduce high salt content of wastewater from lye peeling solution (Schlimme et al., 1984; Wongsa-Ngasri, 2004; Garcia and Barrett, 2006a, 2006b). Enforcement of wastewater discharge regulations due to salinity problems and the problems of large amount of solid waste disposal and wastewater treatment costs have forced the tomato processing industry to look for cost-effective technologies to reduce water usage and wastewater. Some tomato processors have been forced to use steam peeling as an alternative peeling technique in order to reduce chemical contamination in wastewater (Floros and Chinnan, 1988; Setty et al., 1993; Garcia and Barrett, 2006a; Broderick, 2008). However, steam peeling results in deteriorated product appearance, higher loss in firmness, and lower yield compared to the regular lye peeling method (Garcia and Barrett, 2006a). Alternative peeling techniques such as enzymatic peeling, flame-peeling, vacuum-peeling, acid-peeling, freeze-peeling, calcium chloride peeling, and peeling with ohmic heating have been studied on different fruits and vegetables (Rouhana and Mannheim, 1994; Ben-Shalom and Pinto, 1986; Pretel et al., 1997; Toker and Bayndrl, 2003). Other researchers have also studied modified conventional methods, such as high pressure steam peeling with flash cooling, lye-steam peeling, dry-caustic peeling, and freeze-heat peeling (Smith et al., 1980). However, successful commercialization of these methods has been hampered so far because of high equipment and processing costs or other reasons.

Infrared radiation (IR) is energy in the electromagnetic wave form and can be used for thermal processing of foodstuff (Pan et al., 2008). Our investigations have recently demonstrated the potential of using IR as an alternative and sustainable tomato peeling technology (Li et al., 2009). Basically, tomato loosening involves the loss of rigidity and separation of several cell layers between exocarp and mesocarp due to the breakdown of pectin and the formation of cracks on the tomato surface because of the reduced skin strength. In IR peeling, thermal effects are expected to dominate the releasing of the skin although the exact mechanism is still a subject of our investigation. This is mechanistically contrary to the traditional lye peeling whereby the lye solution penetrates the skin and dissolves the pectic and hemicellulosic material in the cell walls via diffusion and removes the pectin which results in the weakening of the network of cell wall and causes the releasing of the skin easy (Das and Barringer, 2005).

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Because of the moist and porous characteristics of tomatoes they are penetrated by radiation to some depth and the IR transmissivity depends on the fruit moisture content (Lampinen et al., 1991). Hashimoto et al. (1990, 1994) studied the penetration of far infrared radiation (FIR) energy and found that FIR absorbed by vegetable food models was damped to 1% of the initial values at a depth of 0.26 to 0.36 mm below the surface. Sakai and Hanzawa (1994) reported that FIR energy penetrates very little and almost all the energy is converted to heat at the surface of food material. Ginzburg (1969) also studied the penetration depth of IR energy into various food products including tomatoes. Because of the high heat delivery capability and low penetration depth, IR becomes a suitable heating method for loosening the tomato skin and thereby peeling of the fruits. Since IR does not need a heating medium for the delivery of energy to the product, such as water, the process was named as "dry peeling" by Hart et al. (1970). The application of IR dry-caustic peeling was studied for white potatoes and peaches and the results exhibited significant decreases in peeling loss, usage of caustic lye and generation of wastewater (Sproul et al., 1975).

IR heating technology has not been widely used for processing agricultural and food products even though many advantages of IR heating have been reported. Limited information regarding the application of IR technology especially in the agricultural and food industry has been the major obstacle in optimizing the design of relevant IR processing equipment and their industrial adoption. The goal of this research was to develop a novel IR peeling method as an alternative peeling technology to current ones so as to produce high quality peeled tomatoes in a cost-effective and environmentally friendly manner. The specific objectives of this study were to (1) investigate the efficacy of using IR for tomato peeling and determine the effect of processing conditions on the peeling performance and product quality; (2) compare the peeling performance and product quality of IR peeling with traditional lye peeling method; and (3) study the synergistic effect on peeling by using low concentration of lye as a pretreatment prior to IR heating.

Materials and Methods

Materials

Due to the variance in harvest time of different cultivars of tomatoes, three commonly grown cultivars (cvs.), Sun6366, CXD179 and AB2, of processing tomatoes (Lycopersicon Esculentum) were used for this study. They were grown by a commercial grower (Button & Turkovich Co., Winters, Calif.) in 2008 season and were hand harvested at red-ripening stage. Tomatoes considered to have defects based on visual observation were eliminated and only tomatoes with uniform sizes were used in the experiments. Tomatoes were washed by tap water and their surfaces were dried with paper towels. In order to avoid chilling injuries, tomatoes were stored no longer than 4 days in an incubator at 11±1°C before being used for the peeling study. Due to high variation in weight, tomatoes that fell into the range of 70 to 110 g were used. The diameter of tomatoes at the largest transverse section was measured and the average was found to be 49±3 mm. The average height of tomatoes, which was determined from the stem scar to the blossom end, was 63±9 mm. Different tomatoes cultivars were used for different sets of tests depending on their harvest date and experimental schedule.

Peeling Performance and Product Quality Evaluation

Peeling Performance

The ease of peeling was evaluated according to Mohr (1990) with some modification. The grading system based on a scale of 1 (unable to peel) to 5 (easy to peel), was used to describe the easiness of peeling of tomatoes heated under different conditions (table 1). A score greater than 4 was considered as an acceptable level for peeling easiness. This method is considered to be more sensitive compared to other mechanical evaluation methods for evaluation of peel loosening.

Peelability was used to determine the degree of peel removal and calculated as un-removed peel per unit weight (cm^2/g). According to FDA standard (21CFR 155.190), un-removed peel per gram of the raw product should be less than 0.015 cm^2/g. This value was used in this study as a standard to determine whether the tomatoes were fully peeled or not. To measure the peelability, the residual skins on each peeled tomato were removed with a knife and then were aligned onto the grids of a sheet having each squared mesh of 9 mm^2. The number of meshes was used to calculate the area of the residual peel.

Peeling loss, the weight change of tomato before and after peeling in terms of percentage, was used to determine the amount of tomato that was removed as by-product or waste (Garcia and Barrett, 2006a). It is desirable to have a low peeling loss from a peeling process.

Product Quality

Texture is one of the most important quality indicators of peeled tomatoes. A procedure developed in the Plant Science Department at University of California Davis was used to characterize the firmness of tomatoes (Cantwell, 2006). The firmness of tomatoes (N) was measured using a fruit texture analyzer FTA GS-14 (Texture Technologies Corp., Scarsdale, N.Y.) through a compression test. A 25-mm diameter probe with flat surface was used to compress the horizontally aligned whole peeled tomato to a distance of 5 mm under 5-mm/s forward speed. The color of peeled tomato was also measured at three different locations along the transverse direction. Tomato color was determined in L^* a^*b^* color space using Minolta Chroma Meter CR200

Table 1. Definitions of peeling easiness.

Grade Scale	Description
1	Removal of the peel is too difficult; some areas fail to peel off or large amount of flesh remains on skin
2	Removal of the peel is difficult in most area of tomatoes; certain areas may not be peeled off
3	Removal of the peel is possible but some difficulties may exist at certain locations
4	Removal of the peel is possible with little effort; large piece of peels can be removed smoothly
5	Removal of the peel is possible without any difficulty; large piece of peels can be removed quickly and smoothly

(Minolta Crop., Ramsey, N.J.). According to Cantwell (2006), Hue° is considered to be the most appropriate value to measure tomato color rather than the individual chromatic components. Hue° was calculated using equation 1:

$$Hue^\circ = \tan^{-1}\left(\frac{b*}{a*}\right) \quad (1)$$

Surface Temperature

The surface temperature of tomatoes was an important processing parameter related to peel-loosening and degradation of pectin under tomato skin. Thus, the skin temperatures of the tomatoes at various IR heating times were measured using a non-contact IR thermometer (Lesman Instrument Company, Bensenville, Ill.). The reported temperature was the mean value of temperatures at four different positions on each tomato (two on the sides, one on blossom end, and one on stem scar). For lye peeling, the surface temperature of tomatoes was assumed to be equal to the temperature of peeling solution.

Experimental Design

IR Peeling

Regular lye peeling with NaOH was used as a control for the IR peeling. Tomatoes were dipped into 10% (w/v) NaOH solution at 95±2°C for 30, 45, 60, and 75 s to simulate the typical industrial operation. The ratio of lye solution to tomato was 5:1. In order to prevent any cooking effect due to heating by the peeling solution, tomatoes were then submerged into a beaker containing tap water at room temperature for 30 s after the heating.

An IR heating system equipped with two catalytic IR emitters (Catalytic Drying Technologies LLC, Independence, Kans.), and powered by natural gas, was used in this research. The IR emitter has a heating surface of 300 × 600 mm. A custom-designed circular metal holder attached to a screw rod was used to place tomatoes between the vertically aligned emitters. The screw rod enabled the horizontal rotation of tomato for 90° every 15 s to improve heating uniformity. The schematic of the experimental device is shown in figure 1. Based on our preliminary tests the distance between the emitters significantly affected the peeling loss and peeling performance, thus the distances between the emitters were selected as 90±2mm, 110±2 mm, and 120±2 mm for the tests. Tomatoes were heated with IR for 30, 45, 60, and 75 s. The rotation effect on the product quality and the peeling performance were investigated.

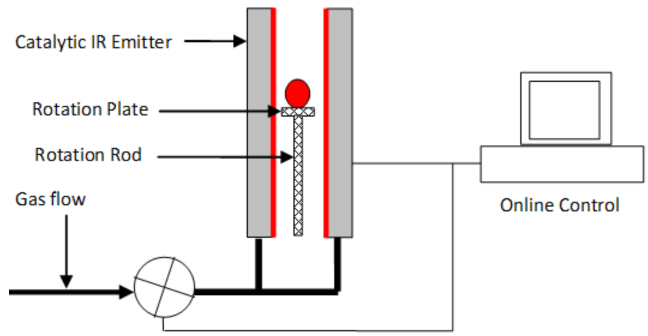

Figure 1. Schematic diagram for IR heating system for tomato peeling.

Lye-IR Peeling

To determine if low lye peeling can be used as a pretreatment of IR heating, the sequential lye (3% NaOH) and IR peeling was tested. Tomatoes were first heated in 3% NaOH solution for 30 s at 95±2°C and then were treated by IR for 30 and 45 s. The gap between emitters was kept at 90 mm and tomatoes were rotated 90° horizontally every 15 s.

Statistical Analysis

Analysis of variance (ANOVA) and mean separation by Duncan's multiple range tests (p≤0.05) were applied to compare the treatments using SAS software package (SAS Institute, 1992). All reported values are the average of ten replicates. All tests were completely randomized so as to obtain independent observations.

Results

IR Peeling

Lye peeling of control samples

For cv. Sun6366 the ease of peeling and peeling loss increased with the increase of dipping time for lye peeling (table 2). Even though all dipping treatments met the 0.015-cm^2/g requirement of peelability standard, we observed that at least 45 s is needed to achieve acceptable level of the easiness of peeling. In contrast, the cv. CXD179 needed less dipping time to achieve a similar easiness of peeling and showed a higher firmness. The firmness did not change much when the easiness was above level 4. The colors of the tomatoes were relatively stable under different heating

Table 2. Effects of lye peeling time on quality and peeling performance for tomato varieties of Sun6366 and CXD179.

Cultivar	Methods and Conditions	Peelability (cm^2/g)	Ease of Peeling[b]	Peeling Loss (%)	Peeled Color (Hue°)	Peeled Firmness (N)
Sun6366	Lye_{10}[a] - 30s	0.004	3.5a	11.5	29.1	14.7a
	Lye_{10} - 45s	0.008	4.1a,b	11.7	29.4	12.7b
	Lye_{10} - 60s	0.004	4.7 b	13.4	29.5	13.7b
	Lye_{10} - 75s	0.003	4.9c	13.6	29.6	12.7b
CXD179	Lye_{10} - 30s	0.007	4.3	10.7	31.5	16.7
	Lye_{10} 45s	0.002	4.5	12.7	30.0	16.7

[a] Subscript 10 of Lye_{10} indicates the percentage of lye concentration in the lye solution.
[b] Means with a different letters in each column for each variety are significantly different at P < 0.05 level.

durations. The results indicated that different varieties had different peeling performances and product qualities.

IR Peeling of Tomato Cv. Sun6366

When IR was used for peeling with an emitter distance of 120 mm (table 3), the required IR heating time to achieve an ease of peeling score above 4 was 60 s which was about 15 s longer than the lye peeling. Compared to the control, the IR peeled tomatoes had much firmer texture and much less peeling loss, such as when the ease of peeling was above 4, the IR and lye peeled tomatoes had firmnesses of 14.7-17.5 and 12.7-13.7 N, respectively, and the corresponding peeling losses of 7.3-9.8% and 11.7-13.6%. All peeled products met the standard of peelability. In general, the rotation seemed to improve both the easiness of peeling and firmness and also reduced peeling loss, but did not have significant effect (P<0.05) on peeling performance and product quality. Because of the parallel configuration of the emitters used in this experiment, rotating the tomato facilitated uniform surface heating of the tomato and thereby the penetration IR into the tomatoes to achieve minimum heating time. For industrial production, it might be possible to adopt a different configuration of IR emitters to eliminate the need of tomato rotation to achieve uniform heating of the tomato surface.

IR Peeling of Tomato cv. CXD179

For cv. CXD179, all IR peeled tomatoes met the peelability requirement (table 4). The heating rate and firmness of peeled products were improved when the emitter gap was reduced from 110 to 90 mm. Therefore, in order to provide higher heat fluxes to rapidly heat the surface of tomatoes, relatively smaller gap between emitters is generally recommended, but consideration should be given to cultivar differences as indicated by comparing the data on product surface temperature following IR heating (tables 3 and 4). For instance, the surface temperature of the tomato was 75°C for emitter gap of 120 and 90 mm for Sun6366 and CXD 179, respectively. The easiness value of peeling reached to 4.8 and was significantly higher (P<0.05) than the control (4.5) when heating time was 45 s. However, the firmness of IR peeled tomatoes was in the range of 12.7 to 15.7 N, while the control gave 16.7 N for both results in table 2. The lower firmness of IR peeled tomatoes could be due to long exposure to IR heating. The average peeling loss of IR treated tomatoes was approximately 9% which was significantly lower (P<0.05) than that of control which was around 10.7%. The difference in peeling loss might be much greater when the peels are removed by a mechanical peel eliminator in the industry. The color of IR peeled tomatoes was similar to the control.

Sequential Lye-IR Peeling of Tomato cv. AB2

Tomatoes of cv. AB2 were used to determine whether the low concentration lye peeling can be used as a pretreatment prior to IR heating for reducing the IR heating time (table 5). To produce control samples, tomatoes were treated with 10% and 3% NaOH solutions for 30 and 45 s, respectively. It was observed that the concentration of lye solution did not have significant effect (P<0.05) on both the peeling performance and product quality. The value of peeling easiness increased with the IR heating time. For example, when the IR heating time was 45 s, the value of ease of IR peeling reached 4.7 compared to 3.9-4.0 of lye peeling. IR peeling also showed significantly lower (P<0.05) peeling loss. The lowered firmness of IR peeling might be due to excessive heating, which should be further studied.

Pretreatment of tomatoes with lye solution for 30 s prior to IR heating of 30 and 45 s increased the values of ease of peeling to 4.8. The sequential treatment with 30-s IR heating resulted in higher firmness than that with 45-s heating. However, the peeling loss from the sequential heating increased significantly (P<0.05) compared to IR heating alone. It was observed that application of low concentration lye peeling was an effective method for reducing IR heating time when IR heating time was 30 s. However, the total time of the sequential method was much longer than the IR treatment alone to achieve same level of ease of peeling.

Table 3. Effects of time and rotation on tomato peeling with IR for tomato variety of Sun6366.

Responses	Time (s)	Rotation with 120-mm Gap		Mean[a]
		Yes	No	
Peelability (cm^2/g)				
	30	0.012±0.013	0.028±0.048	0.020a
	45	0.002±0.002	0.006±0.004	0.004b
	60	0.001±0.001	0.004±0.006	0.002b
	75	0.001±0.002	0.002±0.003	0.002b
	Mean	0.004	0.010	
Ease of peeling				
	30	1.8±1.0	1.4±0.5	1.6a
	45	2.9±0.7	3.0±0.7	3.0b
	60	4.1±0.9	4.0±0.9	4.1c
	75	4.8±0.4	4.3±0.5	4.6d
	Mean	3.4	3.2	
Peeling loss (%)				
	30	7.4±3.0	7.9±2.8	7.6a
	45	5.2±1.1	7.1±1.1	6.1b
	60	7.3±1.3	8.2±1.5	7.7b
	75	9.8±2.2	9.0±1.9	9.4b
	Mean	7.4	8.1	
Peeled color (Hue°)				
	30	27.4±3.3	26.6±2.4	27.0
	45	25.2±2.1	26.6±2.2	25.9
	60	26.9±5.1	26.5±2.6	26.7
	75	29.5±3.1	28.4±2.7	28.9
	Mean	27.5	27.1	
Peeled firmness (N)				
	30	17.6±3.9	17.6±4.9	17.6 a
	45	17.6±4.9	17.6±2.9	17.6 a
	60	14.7±4.9	13.7±3.9	14.7 a,b
	75	17.6±3.9	13.7±2.9	15.7 b
	Mean	16.7	15.7	
Surface temperature (°C)				
	30	58±4	58±5	57. 9a
	45	65±4	67±4	66.2b
	60	70±7	71±5	70.1c
	75	75±4	78±6	76.6d
	Mean	67.0	68.4	

[a] Overall mean separation was via Duncan's Multiple Range Test. Different letters in section indicate significant effects of time at P < 0.05 level.

Table 4. Effect of time and emitter gap on tomato peeling using IR heating for CXD 179. [a]

Responses	Time (s)	90-mm Gap: With Rotation	90-mm Gap: Without Rotation	110-mm Gap: With Rotation	110-mm Gap: Without Rotation	Mean
Peelability (cm^2/g)	45	0.002±0.005	0.000±0.000	0.000±0.001	0.001±0.001	0.001
	60	0.001±0.004	0.000±0.000	0.001±0.004	0.001±0.003	0.001
	75	0.000±0.001	0.000±0.000	0.001±0.002	0.000±0.001	0.000
		90-mm Gap		110-mm Gap		
	Mean	0.001		0.001		
		With Rotation		Without Rotation		
	Mean	0.001		0.000		
Easiness of peeling	45	4.8±0.4	4.4±0.7	4.2±0.8	3.8±0.4	4.3a
	60	5.0±0.0	4.9±0.3	4.8±0.4	4.0±0.7	4.7b
	75	5.0±0.0	5.0±0.0	4.8±0.4	4.6±0.5	4.9b
		90-mm Gap		110-mm Gap		
	Mean	4.9A		4.4B		
		With Rotation		Without Rotation		
	Mean	4.8A		4.5B		
Peeling loss (%)	45	8.8±1.3	8.4±1.5	8.1±1.1	9. 7±1.3	8.7
	60	9.3±1.3	8.8±1.8	8.6±1.3	9. 8±1.7	9.1
	75	9.8±1.9	8.6±1.2	9.6±1.2	9.0±1.8	9.2
		90-mm Gap		110-mm Gap		
	Mean	8.9		9.1		
		With Rotation		Without Rotation		
	Mean	9.01		8.99		
Peeled color (Hue°)	45	32.1±6.7	30.2±6.0	26.8±3.4	31.2±5.8	30.1
	60	33.3±6.2	35.1±11.5	27.0±2.1	31.0±1.9	31.6
	75	30.8±4.3	31.4±3.4	30.0±5.1	29.0±1.8	30.3
		90-mm Gap		110-mm Gap		
	Mean	32.2		29.2		
		With Rotation		Without Rotation		
	Mean	30.0		31.3		
Peeled firmness (N)	45	13.7±3.9	14.7±2.0	15.7±3.9	13.7±2.9	14.7
	60	13.7±4.9	14.7±2.0	15.7±3.9	14.7±2.9	14.7
	75	12.7±2.9	14.7±2.9	14.7±2.9	13.7±2.9	13.7
		90-mm Gap		110-mm Gap		
	Mean	14.7		13.7		
		With Rotation		Without Rotation		
	Mean	14.7		14.7		
Surface temperature (°C)	45	69±6	66±5	61±3	62±3	64.4a
	60	71±3	69±5	67±5	66±3	68.3b
	75	75±4	71±3	73±4	68±6	71.6c
		90-mm Gap		110-mm Gap		
	Mean	70.1A		66.1B		
		With Rotation		Without Rotation		
	Mean	69.2A		66.9B		

[a] Overall mean separation was via Duncan's Multiple Range Test. Different letters in column of the same section indicate significant effects of time at $P < 0.05$ level. Different capital letters in the same row indicate significant difference caused by the gap and rotation at < 0.05 level.

Therefore, considering the processing efficiency and complexity, the sequential heating method is not recommended.

DISCUSSION

Currently, the urgency of a dry-peeling system for the tomato industry can not be underestimated. The findings in this study are a significant step towards an industrial IR dry-peeling system. To develop a scaled-up IR dry-peeling system, fundamental information on the effects of the engineering parameters of IR heating on the peeling performance and product quality are vital. Whereas our primary focus first sought to clarify the above factors, we aimed at providing a prototype industrially applicable IR dry-peeling system. There is still a crucial need to improve

Table 5. Effect of lye-IR peeling on tomato cv. AB2 with emitter gap of 90mm.

Methods and Conditions[a]	Peelability (cm^2/g)	Ease of Peeling	Peeling Loss (%)	Peeled Color (Hue°)[b]	Peeled Firmness (N)	Surface Temperature (°C)
Lye_3 - 30s	0.001	3.6	10.5	31.9	17.6	95
Lye_{10} - 30s	0.013	3.5	10.0	29.9	16.7	95
Lye_3 - 45s	0.003	4.0	10.8	31.0	17.6	95
Lye_{10} - 45s	0.002	3.9	9.5	29.5	20.6	95
IR_{90} - 30 s RTN	0.002	3.0a	8.3	32.2	13.7	58.4a
IR_{90} - 45 s RTN	0.001	4.7b	8.8	33.3	12.7	67.8b
IR_{90} - 75 s RTN	0.001	5.0b	8.6	29.4	14.7	75.8c
Lye_3 + IR_{90} 30 s RTN	0.002	4.8	11.4	29.4a	18.6a	61.1a
Lye_3 + IR_{90} 45 s RTN	0.000	4.8	11.5	35.0b	14.7b	68.1b

[a] Subscript 90 of IR_{90} stands for the gap between the two IR emitters and RTN means with rotation. Subscript 3 of Lye_3 and 10 of Lye_{10} stand for the concentration of the lye solution.

[b] Means with a different letter in each column and the same section are significantly different at $P < 0.05$ level.

on the current configuration of emitters to provide uniform surface heating of the tomatoes and to achieve the industrially acceptable throughput.

It is expected that the cost and benefits related to the new IR dry-peeling method will be more attractive for the commercialization of the IR dry-peeling technology against the presently industrialized lye and steam peeling methods. At a glance, the energy saving resulting from IR dry-peeling is expected to be higher than the current methods (Masanet et al., 2008). For instance, in 2007 the California processing tomato production reached 12.4 million tons and represented 94% of the national production; more than 25% of the total tomato products were peeled for the domestic market and exported as canned or diced tomatoes. During the tomato processing 20% to 25% of solids typically ends up in the waste-stream during lye and steam peeling operations, which accounts for 775,000 tons of solid in the waste-stream. The cost of managing total dissolved solids at the processing plants by various means range from $258 per ton to over $8,000 per ton. Assuming an average cost of $300 per ton, the total cost of treating the wastes from the peeling processes could be $233 million, which could be potentially avoided. Moreover, the new IR dry-peeling method could significantly reduce the current use of over 62,000 acre-feet of water per year by the fruit and vegetable processors in California. The new peeling method would lead to a huge saving in water and water-related energy usage which currently is approximately 20% of the state's electricity, and 30% of the state's non-power plant natural gas.

Conclusion

The feasibility of using infrared radiation (IR) and lye-IR peeling methods as novel alternatives for sustainable peeling of tomatoes was studied and the results were compared with regular lye peeling alone as the control. The following conclusions were drawn:

- IR dry-peeling method gave lesser peeling losses (5.2%-9.8%) than the typical lye peeling (10.7%-13.6%) and either similar or slightly firmer texture in order to achieve the same degree of peelability (<0.015cm^2/g), peeling easiness (>4.0) and heating time range of 30 to 75 s for the tomato cultivars considered in this study.
- Reducing the gap between the emitters (from 120 to 90 mm), thereby increasing the IR intensity, improved heating rate and reduced heating time for achieving the desired peeling performance and product quality which varied with different tomato varieties.
- The rotation of tomatoes under the tested emitter configuration (90- to 120-mm emitter gap and the emitters positioned parallel to the tomato longitudinal axis) slightly improved the peeling performance. Therefore, for industrial production the need to achieve uniform heating of tomato surface is crucial.
- The pretreatment with lye solution prior to IR heating improved the ease of peeling but contrarily lowered the product quality and caused higher peeling loss. Therefore, IR peeling alone is suggested as the best alternative to regular tomato lye peeling and further study is needed for its implementation in the tomato processing industry.

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