Effect of Ionizing Radiation on Furan Formation in Fresh-Cut Fruits and Vegetables

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ABSTRACT: Furan, a possible carcinogen, is commonly induced by thermal processing in a wide variety of foods. The possible formation of furan from fresh-cut fruits and vegetables due to irradiation was studied. Nineteen fresh-cut fruits and vegetables were irradiated by 5 kGy gamma rays at 4 °C. Furan was analyzed from the irradiated samples using a number of preparation methods. The results showed that almost all tested fruits and vegetables, upon irradiation, produced nondetectable levels, or less than 1 ng/g of furan. Irradiation induced low ng/g levels of furan only in grape and pineapple. Dipping apple slices into calcium ascorbate before irradiation did not increase furan formation. The pH and the amount of simple sugars in fresh fruits and vegetables had a role in furan formation. Low levels of furan were induced by irradiation only in those fruits that had a high amount of simple sugars and low pH.

Keywords: ascorbic acid, furan, irradiation, pH, produce, sugars

Introduction

Furan (C_4H_4O) is regarded as a possible carcinogen by the U.S. Dept. of Health and Human Services and the Intl. Agency for Research on Cancer because it causes cancer in animals in studies where the animals are exposed to furan (IARC 1995; NTP 2004). This compound is commonly found in foods that have been treated with traditional heating techniques, such as cooking, jarring, and canning (FDA 2004a; Locas and Yaylayan 2004). As a result, both the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority are requesting data and information about furan formation and its toxicity (FDA 2004b; EFSA 2006). Earlier studies showed that ionizing radiation, a nonthermal processing technology, can induce low ppb levels of furan in solutions of simple sugars and ascorbic acid as well as in fruit juice (Fan 2005a, 2005b). The sources of furan upon irradiation are simple sugars such as fructose sucrose and glucose and ascorbic acid. Many fruits and vegetables are rich in sugars and ascorbic acid. However, whether furan is induced by irradiation in fresh produce is not known.

Currently, irradiation is permitted for use on fresh fruits and vegetables for disinfestation and to inhibit sprouting and maturation at a maximum dose of 1 kGy. However, FDA is considering a petition that requests use of irradiation on both fresh and fresh-cut fruits and vegetables at a maximum dose of 4.5 kGy (FDA 2000). Furan in irradiated foods is one of the issues that FDA is interested in (Pauli 2006).

Furan is a volatile compound that has a boiling point of 31.4 °C. Therefore, furan can evaporate from fresh produce if not packaged in sealed containers and if stored at ambient temperatures, which is the case for many types of whole produce. As a result, furan may not be a concern in irradiated whole produce. However, almost all fresh-cut fruits and vegetables are stored at low temperature and packaged in film bags or thick-wall (clamshell) containers which may prevent diffusion and evaporation of furan if formed. This study was conducted to determine whether furan is induced by irradiation in fresh-cut fruits and vegetables and, if produced, what levels of furan are found in irradiated produce.

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Materials and Methods

Materials

Fresh or fresh-cut fruits and vegetables were purchased from local supermarkets. Fruits included apple, pineapple, grape, banana, strawberry, watermelon, cantaloupe, and honeydew melon, while the vegetables were green pepper, broccoli, carrot, celery, iceberg lettuce, romaine lettuce, red cabbage, snap pea, spinach, tomato, and button mushroom. These fruits and vegetables were chosen because of their economic importance or their common use by the fresh-cut produce industry.

Sample preparation

Method 1. Whether irradiation could induce furan in finely cut fruits and vegetables was first tested. To do this, all samples were cut into small pieces (1 × 1 cm) except for grapes, carrots, and cabbage. For carrots and red cabbage, shredded samples purchased from supermarkets were further cut into short length (approximately 1 cm). Grapes were stripped from their stems and cut into halves. The samples (approximately 5 g) were then placed into 40-mL vials which were sealed using septa and caps and cooled on ice for 2 to 3 h. The samples in the sealed vials were then irradiated with 5 kGy gamma radiation at 4 °C. After irradiation, the samples were incubated at 35 °C water bath for 25 min on a Corning heat/stir plate (Supelco, Bellefonte, Pa., U.S.A.) prior to insertion of a solid phase microextraction (SPME) fiber (85 μm Carboxen-PDMS) into the headspace of the vials. After 20 min of extraction time, the SPME fiber was inserted into the GC as described later. In this test, most of the samples were cut into pieces that were smaller than those commonly used by the fresh-cut industry.

Method 2. In the 2nd experiment, samples with similar sizes as commercial products were used. For apple (cv Gala), fruit was cut into 8 equal pieces without cores. For grape, fruit was taken from the stems without cutting. After removing the skins and cores, pineapple fruit was cut into chunks with a sharp stainless knife. Banana fruit was peeled and cut into pieces (approximately

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3 cm long). For melons, after rind removal, flesh was cut into 3 × 3 cm chunks. Lettuces were cut into 3-cm strips. Celery sticks were cut into approximately 2-cm-long pieces. Baby spinach leaves and snow peas were used without further processing. Fresh-cut broccoli was prepared using only florets without major stalks. Tomato fruit was cut into wedges, while strawberries were cut into halves. Green pepper and mushroom were cut into slices. For carrot and red cabbage, commercial shredded fresh-cut produce were used without further preparation. The fresh-cut fruits and vegetables (100 g) were placed into 500-mL glass jars and sealed using lids. The samples in the jars were cooled down to 4 °C by placing on ice for 4 to 5 h in an insulated container before being exposed to 5 kGy radiation at 4 °C. After irradiation, the samples were spiked with 200 μL 1 ppm d_4-furan and then placed in ambient temperature (approximately 23 °C) overnight before SPME fiber was inserted into the jar through the septa on the lids. After 20-min adsorption, the SPME fiber was injected into GC. We found that the jars needed to stay at approximately 23 °C for at least 5 h for furan to reach equilibrium, and furan levels were maintained for up to 2 d in the jars without significant decreases in furan levels.

Method 3. Even though the above 2 methods could be used to detect whether furan was induced by irradiation, the amount of furan produced by irradiation was unknown. To quantify furan, the FDA method was used, which called for homogenization of samples in water (FDA 2004a; Nyman and others 2006). Fresh-cut samples, as prepared and irradiated in method 2, were cut into 3 × 4 mm pieces on a stainless steel board set on ice. The samples were transferred to a stainless steel cup immersed in an ice bath. Then 10 g cut samples were homogenized in 10 mL cold water (4 °C) using a homogenizer (Virtishear, Virtis, Gardiner, N.Y., U.S.A.) at 21000 rpm for 30 s. The samples were spiked with 10 ppb d_4-furan (as an internal standard) before homogenization. During homogenization, the stainless steel cup that held the samples was surrounded by ice water. Then the homogenate was placed into 40 mL vials with stir bars. After being capped, the vials were incubated at 35 °C for 25 min before SPME fiber was inserted for 20 min. The fiber was injected into GC-MSD for furan analysis. Furan was quantified by comparing with standard curves established in the same homogenate prepared from corresponding nonirradiated produce.

Method 4. Since some furan was evaporated during homogenization, another method was used. Samples as prepared in method 2 were further cut into small pieces (3 × 4 mm) on ice. The samples (10 g) were then placed into 40-mL vials along with 10 mL cold water and d_4-furan (10 ppb final concentration). The vials were sealed and vortexed followed by incubation at 35 °C for 25 min before SPME fiber was inserted into the vials. After 20-min adsorption, SPME fiber was injected into GC-MSD for furan analysis. Furan was quantified by comparing with standard curves established in the same mixtures prepared from corresponding nonirradiated produce.

Method 5. Samples (10 g) were prepared and irradiated in the 40-mL vials in the same way as in method 1. After irradiation, 10 mL cold water (4 °C) was injected, along with d_4-furan, into the vials through the septum without opening of the vials. The vials were vortexed and incubated at 35 °C for 25 min before furan analysis. Furan was quantified by comparing with standard curves established in the same mixtures prepared from corresponding nonirradiated produce.

Furan analysis

Furan was analyzed as described previously (Fan 2005a; Fan and Sommers 2006). Furan was separated and detected by a Hewlett-Packard 5890/5971 GC-MSD (Agilent Technologies, Palo Alto, Calif., U.S.A.) equipped with a 3.5 M GasPro capillary column (0.32 μm i.d.) connected to a DB-5 column (30 m × 0.32 mm i.d., 0.1-μm film thickness, J & W Scientific, Folsom, Calif., U.S.A.) using a Universal Presstight Connecter (Restek Chromatography Products, Bellefonte, Pa., U.S.A.). The injection port was set at 240 °C and the SPME fiber was held in the port for 5 min to desorb volatile compounds. The temperature program of the GC oven was set to 50 °C for 2 min, increased to 130 °C at 10 °C/min, then to 250 °C at 15 °C/min, and held for 2 min at the final temperature. Helium was the carrier gas at a flow rate of 39 cm/s. The transfer line was held at 250 °C during the entire run. Furan and d_4-furan were identified by comparison of spectra of the sample compounds with those of standards and by comparing retention times of sample compounds with those of the standards. The m/z (mass/charge) 39 and 68 and the ratio of 39/68 were used for the confirmation of furan, and m/z 68 was used as the quantifier. The m/z 41 and 72 and the ratio of 41/72 were used for the confirmation of d_4-furan, and m/z 72 was used as the quantifier. Furan was quantified using a standard curve established in individual nonirradiated fruits or vegetables. Nonirradiated materials did not produce detectable furan for any of the 13 types of fresh-cut produce examined in this study. When furan was not quantified (methods 1 and 2), relative levels of furan were expressed as peak area of ion 68.

Effect of Ca ascorbate dipping on furan formation in fresh-cut apples

Apples were cut into 8 equal pieces without core using an apple slicer. The sliced apples were dipped into either water (a control) or 7% calcium ascorbate solution (a concentration commonly used by the industry) for 2 min. The cut apples (150 g) were then drained, placed into the 500 mL glass jars, and sealed. The samples in the jars were then irradiated at 5 kGy at 4 °C. Furan was measured after overnight at 23 °C.

Measurement of soluble solids content, pH, and titratable acidity

Juice was extracted from fresh-cut fruits using a Champion MAR-48C juicer (Plastaket MFG Co., Lodi, Calif., U.S.A.). The juice was stored at −20 °C until analysis. Soluble solids content was measured using a hand-held refractometer (0-30 Brix, Leica, Buffalo, N.Y., U.S.A.). pH was measured using the Orion 420A + pH/mV/ORP meter (Thermo Electron Corp., Beverly, Mass., U.S.A.). Titratable acidity was analyzed by titrating a 5-mL aliquot of juice to pH 8.2 using a TitraLab Titration Workstation TIM-854 autotitrator (Radiometer Analytical, Lyon, France).

Irradiation and dosimetry

The samples were irradiated by 5 kGy gamma rays using a self-contained cesium-137 gamma radiation source (Lockheed Georgia Co., Marietta, Ga., U.S.A.) with an average dose rate of 0.088 kGy/min. The dose (5 kGy) applied on all fresh-cut produce in the present study was similar to the maximum dose (4.5 kGy) petitioned for fresh produce (FDA 2000). Actual doses were verified using alanine dosimeters and found within 10% of targeted dose. Detailed description of irradiation and dosimetry was published earlier (Fan and Sokorai 2002). Temperature of the samples during irradiation was maintained at 4 °C by injecting gas from liquid nitrogen into the irradiation chamber.

Statistical analysis

The experiments were repeated at least 4 times during a 6-month period. Data were subjected to statistical analysis using SAS ver. 8e

(SAS Inst. Inc., Raleigh, N.C., U.S.A.). Duncan's multiple range test was performed using the general linear model procedure.

Results and Discussion

Irradiation (5 kGy) of the small pieces of fruits and vegetables in 40-vials (method 1) induced measurable amount of furan only in 5 types of fruits: grape, pineapple, apple, strawberry, and watermelon (Table 1). Irradiation of grape produced more furan than any other fruits and vegetables. No furan was produced in any vegetable. None of nonirradiated samples produced detectable furan. When fresh-cut produce in larger jars were irradiated (5 kGy) (method 2), furan was detectable in most of the fresh-cut fruits and vegetables (Table 1). Similar to method 1, more furan was induced in grapes followed by pineapples. Unlike in method 1, irradiation induced measurable furan in most of the tested produce using method 2, probably due to a relatively higher amount of samples, which increased furan concentrations in the headspace of the jars. In method 2, all samples were spiked with 200 μL 1 ppm furan-d_4. However, furan-d_4 was not detected in the spiked spinach and mushroom samples, suggesting that furan-d_4 was absorbed by the 2 samples. Nonirradiated apple and tomato also produced detectable furan but not consistently. Among 10 samples of nonirradiated apples and tomatoes, we were able to detect furan only in half of them.

The results in methods 1 and 2 showed that irradiation of grape, pineapple, and some other fruits and vegetables induced furan. However, the amounts of furan accumulated in the fresh-cut fruits and vegetables were unknown. To quantify furan, the samples were homogenized in water after irradiation (method 3). The results using method 3 showed that only grapes produced furan with a level of approximately 2 ng/g (Table 2). No furan was detected in other irradiated fruits and vegetables using this method. Much of the furan may evaporate from fresh-cut produce during homogenization, even though the samples were maintained on/in ice water. To avoid the loss of furan during homogenization, the irradiated samples from the jars were cut into smaller pieces and then mixed with water without homogenization (method 4). The results showed that furan levels in grape and pineapple were 3.2 and 1.7 ng/g, respectively, while apple produced less than 1 ng/g of furan. No detectable amount of furan was found in any other fruits or vegetables. In method 4, some furan could still be lost during cutting and preparation. A method without opening the vials that contained the samples was used (method 5). The results showed that irradiation (5 kGy) induced furan in grape and pineapple with furan levels of 3.6 and 3.0 ng/g, respectively. Apple and strawberry also produced measurable amounts of furan, but with levels below 1 ng/g. No measurable furan was found in other produce.

There were some discrepancies among the methods regarding the amounts of furan in the fresh-cut fruits and vegetables. However, it is consistent among the methods that irradiation of grape and pineapple produced more furan than other fruits and vegetables, and most of the irradiated vegetables did not produce quantifiable furan.

An earlier study showed that furan can be formed from ascorbic acid (Fan 2005a). A calcium salt of ascorbic acid is a common antibrowning agent for several fresh-cut fruits, primarily for apples (Chen and others 1999; Karaibrahimoglu and others 2004). Ascorbic levels in/on apple slices treated with 7% of calcium ascorbate could be 70 times higher than the nontreated ones (Fan and others 2005). It was unclear whether the increased amount of ascorbic acid due to calcium ascorbate dipping resulted in additional

Table 1—Formation of furan (means ± standard errors) in cut fruits and vegetables after 5 kGy gamma radiation. Two types of methods were used to detect furan formation: Method 1: Small sized (< 1 cm) samples (5 g) enclosed in 40-mL vials were irradiated; Method 2: Fresh-cut (3 to 4 cm long) samples (100 g) enclosed in 500 mL jars were irradiated. Relative furan levels were expressed as peak area of ion 68.

	Furan (peak area/1000)			
	Method 1		Method 2	
Produce	0 kGy	5 kGy	0 kGy	5 kGy
Grapes	ND	78 ± 11a	ND	695 ± 291a
Pineapple	ND	12 ± 4b	ND	194 ± 86b
Apples	ND	6 ± 2b	1 ± 1	48 ± 22b
Strawberry	ND	2 ± 1b	ND	8 ± 2b
Banana	ND	ND	ND	7 ± 1b
Watermelon	ND	2 ± 2b	ND	65 ± 37b
Cantaloupe	ND	ND	ND	ND
Honeydew melon	ND	ND	ND	4 ± 3b
Tomato	ND	ND	2 ± 2a	47 ± 34b
Green pepper	ND	ND	ND	13 ± 6b
Broccoli	ND	ND	ND	ND
Carrot	ND	ND	ND	2 ± 2b
Celery	ND	ND	ND	19 ± 11b
Iceberg lettuce	ND	ND	ND	ND
Romaine lettuce	ND	ND	ND	11 ± 6b
Red cabbage	ND	ND	ND	16 ± 8b
Mushroom	ND	ND	ND	16 ± 9b
Snap pea	ND	ND	ND	11 ± 5b
Spinach	ND	ND	ND	16 ± 6b

Means with same letters are not significantly different (Duncan's multiple range test, $P < 0.05$); ND = not detectable.

Table 2—Furan levels (ng/g) of cut fruits and vegetables after 5 kGy gamma radiation. Three methods were used to prepare the samples for furan quantification. Method 3: Fresh-cut samples after irradiation were homogenized in water before furan analysis; Method 4: Fresh-cut samples were further cut into smaller pieces and then mixed with equal amount of water; Method 5: Smaller pieces of samples were directly irradiated followed by mixing with water without opening of the containers. Furan in the mixture or homogenates was quantified against standard curves established in the corresponding matrix of individual fruits and vegetables.

	Furan (ng/g)		
Produce	Method 3	Method 4	Method 5
Grapes	2.0 ± 0.4[a]	3.2 ± 0.6a	3.6 ± 0.9a
Pineapple	ND	1.7 ± 0.8b	3.0 ± 1.2a
Apples	ND	<1.0 b	<1.0b
Strawberry	ND	ND	<1.0b
Banana	ND	ND	ND
Watermelon	ND	ND	ND
Cantaloupe	ND	ND	ND
Honeydew melon	ND	ND	ND
Tomato	ND	ND	ND
Green pepper	ND	ND	ND
Broccoli	ND	ND	ND
Carrot	ND	ND	ND
Celery	ND	ND	ND
Iceberg lettuce	ND	ND	ND
Romaine lettuce	ND	ND	ND
Red cabbage	ND	ND	ND
Mushroom	ND	ND	ND
Snap pea	ND	ND	ND
Spinach	ND	ND	ND

[a]For all 3 methods, the estimated limit of quantitation (LOQ) is 1 ng/g for all fruits and vegetables. Values below the LOQ are reported as <1.0 ppb; ND = not detectable.
Means with same letters are not significantly different (Duncan's multiple range test, $P < 0.05$).

furan formation after irradiation. Therefore, the apple slices were dipped into 7% calcium ascorbate for 2 min before irradiation (5 kGy). The results showed that furan levels in samples dipped in calcium ascorbate were 102 ± 18% of the control (water dipping), suggesting that dipping cut apples into calcium ascorbate solution did not significantly increase the furan formation, probably due to the neutral pH of calcium ascorbate. An earlier study showed that furan was mainly produced from ascorbic acid at low pHs (Fan 2005a). The amount of ascorbic acid on/in sliced apples was much less compared with amounts of sugars (Table 3 and 4), even after being dipped into calcium ascorbate.

More furan was detected in irradiated fruits than in vegetables. The results in the present study showed that irradiation at 5 kGy induced low ng/g levels of furan in grapes and pineapples. Some other fruits that produced less than 1 ng/g furan included apples and strawberries. Irradiation of vegetables produced little furan. Generally, fruits contain higher amounts of sugars than vegetables. In addition, many fruits also have higher acidity and low pH while most vegetables (except tomato) have neutral pHs and lower acidity. An earlier study (Fan 2005a) showed that pH and concentration of sugars and ascorbic acid solutions had profound influences on furan formation due to irradiation. The rate of irradiation-induced furan formation increased with decreasing pH from 8 to 3. Approximately 1600 times less furan was formed at pH 8 as apposed to pH 3. To evaluate possible roles of pH and composition in furan formation in fresh produce, we analyzed pH, soluble solids content, and titratable acidity of the fruits. All fruits contained more than 8% of soluble solids content (Table 3). Grape, pineapple, and apple had the highest soluble solids content while strawberry and banana had the lowest. Grape, pineapple, apple, and strawberry had significantly ($P < 0.05$) higher titratable acidity than other fruits. As a result, the 4 fruits had pHs of 3 to 4, which were significantly lower than other fruits. The fact that furan was quantifiable mostly in those 4 fruits suggests that, in addition to sugar content, pH played an important role in furan formation. Fruits such as banana, watermelon, cantaloupe, and honeydew melon, which contained high amounts of sugars but higher pHs, did not produce quantifiable furan. It seems that furan was produced only in fresh fruits and vegetables that have high sugars and low pH.

Earlier results suggested that at the same pHs, the amounts of furan formed from irradiation of fructose, sucrose, and ascorbic acid were always higher than that from glucose (Fan 2005a). The amounts of sucrose, fructose, and glucose varied considerably among the fresh fruits and vegetables (Table 4). However, there were no apparent correlations between the nature of the simple sugars and irradiation-induced furan. Similarly, the amount of ascorbic acid varied among different fruits and vegetables and did not correlate ($R^2 = 0.0525$, $P > 0.05$) with furan formation.

Some juice (purge, dripping) was accumulated in the bottle of jars that contained watermelon and pineapples. The freestanding juice may contribute to furan formation as irradiation of fruit juice induced low ppb of furan (Fan 2005b). It is unclear whether oxidation of ascorbic acid to dehydroascorbic acid and/or hydrolysis of sucrose to fructose and glucose in freestanding juice play any role in the irradiation-induced furan formation. It has been shown that thermal treatment induced a higher amount of furan from dehydroascorbic acid than from ascorbic acid (Becalski and Seaman 2005). Whether dehydroascorbic acid shows a higher potential to form furan upon irradiation than ascorbic acid needs to be investigated.

Even though a petition asked FDA to approve a maximum dose of 4.5 kGy irradiation for use on fresh produce (FDA 2000), it is unlikely that this high dose would be applied commercially to fresh produce due to adverse effects on produce quality. Many fresh-cut fruits and vegetables can tolerate up to 1 kGy radiation without significant change in quality (Prakash and others 2000; Fan and Sokorai 2005; Niemira and Fan 2005). Some produce may encounter deterioration in quality such as browning and softening if treated with higher doses of radiation. Therefore, considering the low levels

Table 3—Soluble solids content (SSC), pH, and titratable acidity of fresh fruits.

Produce	SSC (%)	pH	Titratable acidity (mg malic acid equivalent/100 mL)
Apple	14.3 ± 0.3b	3.6 ± 0.1f	417 ± 38c
Pineapple	13.2 ± 0.7b	3.3 ± 0.1g	754 ± 81a
Grape	16.7 ± 0.9a	4.0 ± 0.1e	396 ± 35c
Watermelon	9.3 ± 0.2cd	5.5 ± 0.1c	66 ± 3d
Strawberry	8.5 ± 0.3d	3.8 ± 0.1f	633 ± 30b
Banana	8.5 ± 0.1d	5.0 ± 0.1d	158 ± 24d
Cantaloupe	10.5 ± 0.7c	6.4 ± 0.1a	47 ± 11d
Honeydew melon	10.1 ± 0.5cd	5.8 ± 0.1b	109 ± 18d

Means with same letters are not significantly different (Duncan's multiple range test, $P < 0.05$); ND = not detectable.

Table 4—Contents of total sugar, sucrose, glucose, fructose, and ascorbic acid of fresh-cut fruits and vegetables.

Produce	Total sugar (g/100 g)	Sucrose (g/100 g)	Glucose (g/100 g)	Fructose (g/100 g)	Ascorbic acid (mg/100 g)
Apple	10.39	2.07	2.43	5.90	4.6
Pineapple	9.26	5.47	1.74	2.05	36.2
Grape	15.48	0.15	7.20	8.13	10.8
Watermelon	6.20	1.21	1.58	3.36	8.1
Strawberry	4.66	0.12	2.04	2.50	58.8
Banana	12.23	2.39	4.98	4.85	8.7
Cantaloupe	7.86	4.35	1.54	1.87	36.7
Honeydew melon	8.12	2.48	2.68	2.96	18.0
Green pepper	2.40	0.11	1.16	1.12	80.4
Carrots	4.54	3.59	0.59	0.55	5.9
Iceberg lettuce	1.96	0.05	0.91	1.00	2.8
Romaine lettuce	1.19	0	0.39	0.80	24.0
Mushroom	1.65	0	1.48	0.17	2.1
Red cabbage	3.91	0.58	1.80	1.53	57.0
Celery	1.83	0.11	0.55	0.51	3.1
Spinach	0.42	0.07	0.11	0.15	28.1
Broccoli	1.65	0.10	0.49	0.68	93.2
Tomato	2.62	0	1.25	1.37	16.0
Snap pea	4.95	3.58	1.35	0.02	60.0

Data were extracted and calculated from USDA (2007) Nutrient Database and Basterrechea and Hicks (1991).

of furan produced by 5 kGy radiation, irradiation at doses around 1 kGy would produce much less furan. Furan has a boiling point of 31.4 °C. Some fresh-cut fruits and vegetables are packaged in gas permeable film bags that may allow furan to escape during shipping and display, which will result in significantly lower furan levels in the product than the levels reported in the present study. In addition, the levels of furan found in grape and pineapple were much lower than those in some thermal processed foods (FDA 2004a) with furan levels as high as 100 ng/g. Therefore, it appears that furan formation in fresh-cut produce due to irradiation is not a major safety concern.

Conclusions

The results in this study showed that irradiation produced low levels of furan in grape and pineapple. In all other fruits and vegetables, furan levels were not detectable or below 1 ng/g. Soluble solids content, titratable acidity, and pH varied among the fruits. Furan was produced mainly from sugar-rich fruits that had lower pHs. It appears that the presence of high amount of sugars and low pH are prerequisites for furan formation in fresh-cut produce. Considering the low ng/g of furan detected in grape and pineapple as well as the volatility of furan, irradiation-induced furan is unlikely to be a concern for fresh-cut produce.

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