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# Formation of Furan from Carbohydrates and Ascorbic Acid Following Exposure to Ionizing Radiation and Thermal Processing

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This study was conducted to investigate the formation of furan from sugars, ascorbic acid, and organic acids as affected by ionizing radiation and thermal treatments. Results showed that both thermal treatments and irradiation induced formation of furan from ascorbic acid, fructose, sucrose, or glucose. Little furan was produced from malic acid or citric acid. The pH and concentration of sugars and ascorbic acid solutions had profound influences on furan formation due to either irradiation or thermal treatment. 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. At the same pHs, the amounts of furan formed from irradiation of ascorbic acid, fructose, and sucrose were always higher than from glucose. As pH decreased from 7 to 3, an increase in thermally induced furan was observed for sucrose and ascorbic acid solutions, but for glucose solution, less furan was formed at pH 3 than at pH 7. The levels of sugars commonly found in fruits and fruit juices, upon irradiation, would be high enough to potentially produce low parts per billion (ppb) levels of furan. The concentration of ascorbic acid at which a maximum of furan was produced upon irradiation was about 0.5 mg/mL, a level commonly found in some foods. Five furan derivatives were tentatively identified in thermally treated ascorbic acid solution, while one furan derivative was tentatively found in both irradiated and thermally treated samples.

**KEYWORDS: Furan; ionizing radiation; ascorbic acid; fructose; glucose; sucrose; thermal treatment**

## INTRODUCTION

Furan, a colorless volatile compound (*1*), is classified as "reasonably anticipated to be a human pathogen" by the U.S. Department of Health and Human Services (*2*) and as "possibly carcinogenic to humans" by the International Agency for Research on Cancer (*3*). A recent FDA survey found that furan was present in a large number of thermally processed foods, with furan levels of ∼100 ppb in some foods (*4*). Our recent study suggested that ionizing radiation, a nonthermal processing technology, induced furan formation in orange and apple juices (*5*). The amounts of furan formed as a result of irradiation were generally in the low parts per billion (ppb) range.

Fruit juices are rich in carbohydrates and organic acids (*6*). The most common carbohydrates in fruit juices are fructose, sucrose, and glucose. The most dominant organic acids are malic acid and citric acid in apple and orange juices, respectively. In addition, fruit juice is also a good source of ascorbic acid. These compounds may serve as precursors for furan. It is known that the primary sources of thermally produced furan and its derivatives are carbohydrates, such as glucose (*7*) and ascorbic acid (*8*). A recent study by Locas and Yaylayan (*9*) suggested that ascorbic acid had the highest potential to produce furan upon thermal treatment, followed by some sugar/amino acids mixtures. Becalski and Seaman (*10*) identified two pathways of thermally induced furan formation in model systems: the oxidation of poluunsaturated fatty acids and the decomposition of ascorbic acid derivatives. It is unclear whether the formation of furan in fruit juices due to irradiation has similar mechanisms as that of thermal treatment.

The objectives of the present study were to investigate the formation of furan from major components of fruit juices, as affected by ionizing radiation and thermal treatment, and to study substrate concentration and pH effects on the formation of furan.

## MATERIALS AND METHODS

**Chemicals.** L-Ascorbic acid, D-fructose, D-glucose, DL-malic acid and sodium phosphate monobasic were purchased from Sigma-Aldrich (St Louis, MO). Citric acid and sucrose were purchased from Mallinckrodt Laboratory Chemicals (Phillipsburg, NJ). All chemicals had a minimum of 99% purity.

**Dose Response.** Aliquots (5 mL) of solutions containing 50 mg/mL sucrose, glucose, or fructose or 5 mg/mL malic acid, citric acid, or ascorbic acid prepared in deionized water were placed into 15-mL glass vials. The concentrations of carbohydrates and organic acids were

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chosen to simulate fruit juice. The vials were sealed with Teflon-lined septa and screw caps and stored at 5 °C overnight before being irradiated at 5 °C to 0, 2.5, and 5.0 kGy. The samples were spiked with furan-$d_4$ before analysis by the method described below. *G* values (number of species per 100 eV absorbed) were calculated by the following equation (*10*): $G = k \times 10^8$, where *k* is the slope (moles per liter per kilogray) of the linear curve of yield versus dose.

**Irradiation and Dosimetry.** Irradiation was conducted at 5 ± 2 °C in a self-contained, Lockheed Corporation (Marietta, GA) $^{137}$Cs g radiation source. The unit has 23 $^{137}$Cs pencils placed in an annular array around a 63.5-cm-high stainless steel cylindrical chamber with a 22.9-cm internal diameter. The dose rate was 0.091 kGy/min. The dose rate was established by use of alanine transfer dosimeters from the National Institutes of Standards and Technology (Gaithersburg, MD). Actual doses were typically within 5% of targeted doses. The variations in radiation dose absorption were minimized by placing the samples within a uniform area of the radiation field, by irradiating them within a polypropylene container (4-mm wall) to absorb Compton electrons, and by using the same geometry for sample irradiation during the entire study. Routine dosimetry was performed with 5-mm-diameter alanine dosimeters (Bruker Instruments, Rjeomstettem, Germany), and the free-radical signals were measured on a Bruker EMS 104 EPR analyzer. The dosimeters were placed into 1.2 mL cryogenic vials (Nalgene, Rochester, NY), and the cryogenic vials were taped onto the tubes containing samples prior to irradiation. Temperature was maintained by injecting the gas phase from a liquid nitrogen tank into the radiation chamber.

**Measurement of Furan.** Furan was measured by solid-phase microextraction (SPME) coupled with GC-MS as described earlier (*5*). Briefly, immediately after irradiation or thermal treatment, samples in the 15-mL vials were spiked with furan-$d_4$ (as an internal standard) through the septum with a syringe, and then incubated at 35 °C for 25 min in a 15-mL vial holder sitting on a Corning heat/stir plate (Supelco, Bellefonte, PA) before a SPME fiber (75 $\mu$m Carboxen-PDMS) was inserted into the headspace of a vial. After 20 min of incubation, the SPME fiber was then inserted into the GC injection port at 240 °C and held there for 5 min to desorb volatile compounds. Volatile compounds were separated by a Hewlett-Packard 5890/5971 GC-MSD (Agilent Technologies, Palo Alto, CA) equipped with a 3.5 M GasPro capillary column (0.32 mm i.d.) connected to a DB-5 column (30 m × 0.32 mm i.d., 0.1 $\mu$m film thickness, J & W Scientific, Folsom, CA) by use of a Universal Presstight connector (Restek Chromatography Products, Bellefonte, PA). The temperature profile of the GC oven was set to 50 °C for 2 min, increased to 130 °C at 10 °C/min, and 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. The MSD acquisition was set as scan mode. Mass range was 35−300 amu. The electron impact ionization mode was set at an energy of 70 eV. Furan was 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. Furan levels in the samples were calculated from an external standard curve established in water, and adjusted by use of the internal standard (furan-$d_4$).

**Effect of Substrate Concentration on Irradiation-Induced Furan Formation.** A series of concentrations of fructose, glucose, or sucrose (0, 1, 10, 50, and 100 mg/mL) and ascorbic acid (0, 0.05, 0.1, 0.2, 0.5, 5, and 20 mg/mL) were prepared in deionized water. The solutions (5 mL) were then placed into 15-mL glass vials. The vials were sealed, stored at 5 °C overnight, and then irradiated (5.0 kGy) at 5 °C. Furan was then measured as described earlier.

**Effect of pH on Irradiation-Induced Furan Formation.** Carbohydrates and organic acids were dissolved in sodium phosphate solution, and pHs of the solutions were adjusted to 3, 4, 5, 6, 7, and 8 with diluted HCl or NaOH. The final concentration of carbohydrates and ascorbic acid in the solutions were 50 and 5 mg/mL, respectively, while the concentration of sodium phosphate was 50 mM. The solutions were placed into 15-mL vials, cooled to 5 °C, and then exposed to 5 kGy of $\gamma$ radiation at 5 °C. Furan was measured as described earlier.

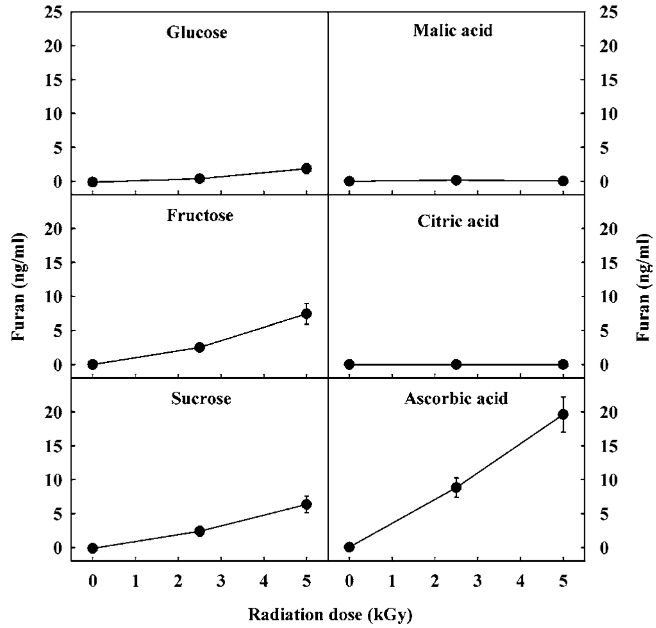


**Figure 1.** Accumulation of furan in solutions of carbohydrates and organic acids as a function of radiation dose. Solutions of glucose, fructose, and sucrose (50 mg/mL each) and malic acid, citric acid, and ascorbic acid (5 mg/mL) were irradiated to 0, 2.5, and 5.0 kGy radiation at 5 °C. Vertical bars represent standard deviation of means ($n = 4$).

**Effect of Thermal Processing on Formation of Furan.** Two types of thermal treatments were employed, simulating pasteurization and sterilization. Aliquots (5 mL) of carbohydrates (50 mg/mL) and organic acid (5 mg/mL) in 15-mL vials, spiked with ~10 ppb furan-$d_4$, were either submerged into boiling water for 5 min or heated to 121 °C by use of a liquid cycle for 25 min in an autoclave (Amsco G120 Eagle/Century series, Steris Corp., Mentor, OH). During treatments, the vials were set upside down to minimize the leakage of furan in headspace. The vials were then cooled rapidly by submerging the vials into ice water for 10 min. Samples without any thermal treatment served as controls. Furan in the samples was then analyzed after equilibration at 5 °C for 1−3 h.

**Effect of pH on Thermally Induced Furan Formation.** Fructose, glucose, or sucrose (50 mg/mL) and ascorbic acid (5 mg/mL) were prepared in 50 mM sodium phosphate with pH adjusted to pH 3 or 7. The solutions (5 mL) in 15-mL glass vials were autoclaved and then cooled. Furan was then measured.

**Statistical Analysis.** The experiments were replicated four times. Data were subjected to statistical analysis by SAS, version 8 (SAS Institute, Cary, NC). Differences between treatments were analyzed by least significant difference (LSD) test using the general linear model. In the figures, mean standard deviations are presented. When the difference between any two treatments is larger than the sum of standard deviations of the two treatments, it was always significant (LSD, $P < 0.05$). Only significant differences were discussed unless stated otherwise.

## RESULTS AND DISCUSSION

**Dose Response.** The accumulation of furan increased with increasing radiation dose in the three carbohydrate solutions and in ascorbic acid solution (**Figure 1**). The furan levels in the irradiated (2.5 and 5.0 kGy) citric acid solution were below the estimated detection limit (0.5 ng/mL), while no furan was detected in irradiated malic acid solution even at 5 kGy. Comparing the three carbohydrates, significantly ($P < 0.05$) higher amounts of furan were formed in fructose and sucrose than glucose. However, the highest amount was found from irradiated ascorbic acid solution. If we expressed the dose response for the furan formation as linear curves in the

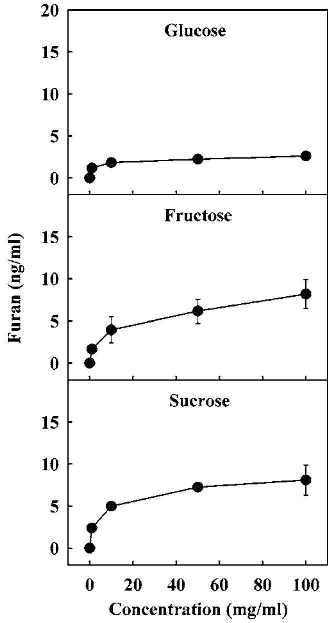


**Figure 2.** Effects of substrate concentration on irradiation-induced accumulation of furan from carbohydrates. A series of concentrations of glucose, fructose, and sucrose solutions were irradiated with 5 kGy $\gamma$ rays at 5 °C. Vertical bars represent standard deviation of means ($n = 4$).

carbohydrates and ascorbic acid solutions ($R^2$ for all curves was above 0.90), then *G*-values (number of furan molecules formed per 100 eV absorbed) could be calculated from the curves. The G-values were 0.48, 2.04, 1.77, and 5.66 for glucose, fructose, sucrose, and ascorbic acid, respectively. Ascorbic acid was significantly ($P < 0.05$) more sensitive to irradiation than the sugars. Among the three sugars, irradiation of glucose produced the least amount of furan. Compared to ascorbic acid, irradiation of dehydroascorbic acid, an oxidized form of ascorbic acid, produced very little furan (data not shown). For example, upon 5 kGy irradiation, ascorbic acid produced about 20 ng/mL furan while dehydroascorbic acid formed only 1 ng/mL furan, an amount less than that from glucose.

**Substrate Concentration on Irradiation-Induced Furan Formation.** The formation of furan due to irradiation increased with increasing concentration of carbohydrates. However, no significant ($P < 0.05$) increase in furan formation was observed when the concentrations of the carbohydrates increased from 50 to 100 mg/mL. The fastest increase for all three sugars was observed at the concentrations ranging from 0 to 5 mg/mL (0−0.5%) (**Figure 2**). As concentrations of sugars further increased, the rate of furan formation decreased. Carbohydrates are major components of many fruits and their products, with a concentration commonly above 0.5% (*6*). The results indicate that the concentrations of sugars commonly found in fruits and fruit juices were high enough to potentially produce a significant amount of furan upon irradiation and were not a limiting factor for the formation of furan.

For ascorbic acid, a rapid increase in furan formation occurred in concentrations ranging from 0 to 0.5 mg/mL (**Figure 3**). Further increase in concentration of ascorbic acid did not significantly ($P > 0.05$) increase furan formation. Most natural foods contain less than 0.5 mg/mL ascorbic acid. For example, orange juice, a high ascorbic acid food, contains about 0.05% (∼0.5 mg/mL) ascorbic acid (*6*). Therefore, it is likely that the amounts of ascorbic acid in fruit juice may limit the formation of furan; that is, foods containing high levels of ascorbic acid will have higher potential to produce furan than those with less ascorbic acid upon irradiation.

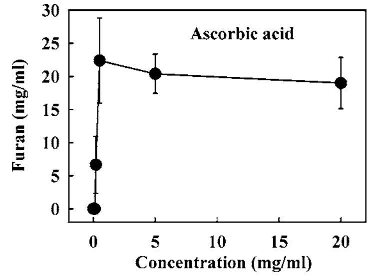


**Figure 3.** Effects of substrate concentration on irradiation-induced accumulation of furan from ascorbic acid. A series of concentrations of ascorbic acid solutions were irradiated with 5 kGy $\gamma$ rays at 5 °C. Vertical bars represent standard deviation of means ($n = 4$).

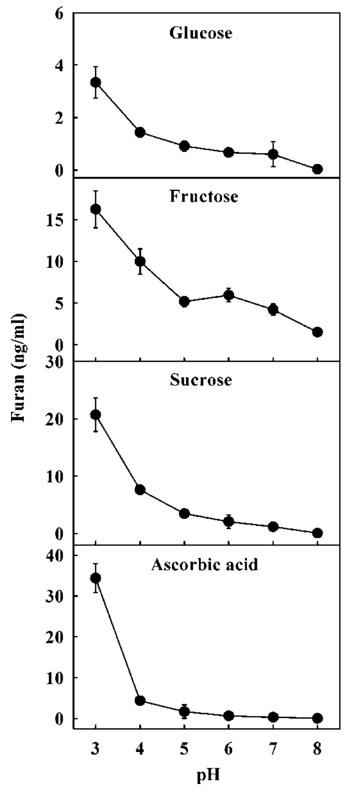


**Figure 4.** Effect of pH on irradiation-induced accumulation of furan from carbohydrates and ascorbic acid. Solutions of glucose, fructose, and sucrose (50 mg/mL each) and ascorbic acid (5 mg/mL) with different pHs were exposed to 5.0 kGy radiation at 5 °C. Vertical bars represent standard deviation of means ($n = 4$).

It should be pointed out that the pHs of the above solutions were not adjusted. The pHs of 50 mg/mL fructose, glucose, and sucrose were approximately 6.4, while the pH of ascorbic acid was about 3.0. pH can be a factor for the formation of furan from these substrates. Therefore, the influence of pH on furan formation was investigated.

**pH Effect on Irradiation-Induced Furan Formation.** The effect of pH on the formation of furan from sugars and ascorbic acid is shown in **Figure 4**. The pH of solutions had a profound effect on the formation of furan due to irradiation. Generally speaking, as pH increased, the formation of furan in sugars and ascorbic acid solution decreased. A rapid reduction in the formation of furan occurred when the pH was increased from 3 to 5, although further increase in pH continued to lower the formation of furan due to irradiation. At neutral pH, much less furan was formed in all solutions compared to pH 3. For

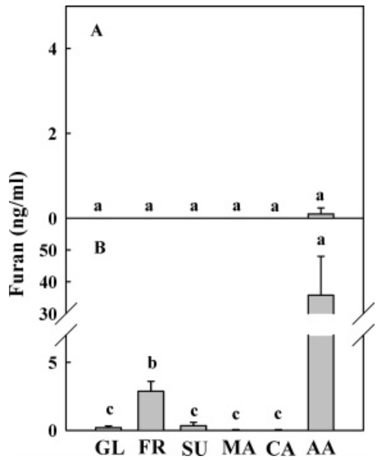


**Figure 5.** Effect of thermal processing on furan formation in solutions of carbohydrates and organic acids. Solutions of glucose (GL), fructose (FR), and sucrose (SU) (50 mg/mL each) and malic acid (MA), citric acid (CA), and ascorbic acid (AA) (5 mg/mL) in 15-mL vials were treated with boiling water for 5 min (**A**) or autoclaved for 25 min (**B**). Vertical bars represent standard deviation of means ($n = 4$). Bars with same letters are not significantly different (LSD, $P < 0.05$). Comparison was made within the same thermal treatment.

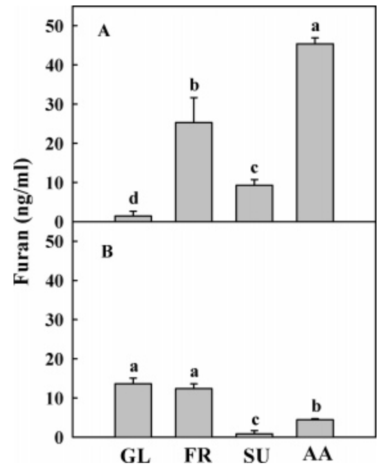


**Figure 6.** Effect of pH on thermal-induced formation of furan from carbohydrates and ascorbic acid. Solutions of glucose (GL), fructose (FR), and sucrose (SU) (50 mg/mL each) and ascorbic acid (AA) (5 mg/mL) with pH 3 (**A**) and 7 (**B**) were prepared in phosphate buffer (50 mM). The solutions were then autoclaved for 25 min. Vertical bars represent standard deviation of means ($n = 4$). Bars with same letters are not significantly different (LSD, $P < 0.05$). Comparison was made within the same pH.

example, irradiation of ascorbic acid at pH 8 produced approximately 1600 times less furan than at pH 3. For fructose solution, the furan formation as a result of irradiation decreased rapidly in the pH range of 3−5, but as pH increased further to 6, there was a leveling off of furan formation, followed by a decrease as pH increased from 6 to 7. It has been shown that pH had similar influence on formation of 2-furfuraldehyde and 2-furancarboxylic acid from dehydroascorbic acid as a result of thermal treatment (*12*). Our earlier results studying irradiation-induced malondialdehyde and formaldehyde formation showed a completely different pattern from that of furan formation; that is, the highest rate of formation of formaldehyde and malondialdehyde was generally observed at pH 7.0 (*13*).

The results suggested that pH had a profound effect on formation of furan from all three sugars and ascorbic acid. In the solutions without pH adjustment, ascorbic acid had the highest potential to produce furan upon irradiation. The high amount of furan formed from ascorbic acid is likely due to the low pH of the solution (pH 3.0) compared to the neutral pH of sugars (pH 6.4). When comparing formation of furan at the same pHs, we found that, at pH 3, irradiation of ascorbic acid produced the highest amount of furan, but at other pHs, irradiation of fructose produced the highest amount of furan. At pH 6−7, irradiation of ascorbic acid produced the least amount of furan. Regardless of pH, irradiation of glucose always produced significantly ($P < 0.05$) less furan than fructose and glucose. The results indicate the importance of pH in solutions or foods for future studies.

**Effect of Thermal Treatments.** Treating the carbohydrate, citric acid, or malic acid solutions in boiling water for 5 min did not result in measurable formation of furan (**Figure 5**). A very small (not significant at $P < 0.05$) amount of furan was formed from ascorbic acid after the thermal treatment. Autoclaving of solutions induced the formation of furan from glucose, fructose, sucrose, and ascorbic acid. Similar to the response to irradiation, the largest amounts of furan were from ascorbic acid and fructose. Significantly ($P < 0.05$) higher amount of furan was formed from ascorbic acid than from fructose, while the amount of furan from fructose was significantly higher than from other sugars and organic acids. Autoclaving of malic acid and citric acid produced little furan. Only a small amount of furan was formed from the autoclaving of glucose and sucrose. It is interesting to note that irradiation of fructose and sucrose solutions produced a similar amount of furan. However, upon autoclaving, much more (about 16 times more) furan was formed from fructose solution than from sucrose solution.

Results reported earlier (*5*) demonstrated that a higher amount of furan was formed in orange juice than in apple juice when heated at 100 °C, while a higher amount of furan was observed in apple juice than orange juice at 121 °C. In addition, orange juice contained much higher levels of ascorbic acid than apple juice, and thermal treatment destroyed much more ascorbic acid in orange juice than in apple juice. The results in the present study indicated that furan was generated only from ascorbic acid when heated at 100 °C. It appears that the higher amount of ascorbic acid generated in orange juice due to heating at 100 °C was a direct result of ascorbic acid degradation. It is possible that, upon autoclaving, furan was formed mainly from carbohydrates that were abundant in fruit juice even though much more ascorbic acid was destroyed at 121 °C than at 100 °C.

Besides the formation of furan, autoclaving of ascorbic acid induced several furan-related compounds. These compounds included 2-furancarboxaldehyde, 2-methylfuran, 2,2′-methylenebis(furan), and 2,2′-bifuran. They were tentatively identified by comparing their spectra with those of Wiley mass spectral database. 2-Furancarboxaldehyde was also found in all autoclaved sugar solutions. Irradiation of ascorbic acid at 5 kGy resulted in the formation of 2-methylfuran, but at levels much smaller than those in autoclaved samples. The amounts of 2-methylfuran due to irradiation were also much less (less than 1 ppb) on the basis of the peak heights compared to that of furan as results of the same treatment. Similar to furan, 2-methylfuran has been found in heated foods (*14*, *15*) and carbohydrates (*1*) and exhibited a clastogenic activity in Chinese hamster ovary cells (*16*).

**Effect of pH on Thermally Induced Furan Formation.** The pH had a significant effect on thermally induced furan formation (**Figure 6**). At pH 3, thermal treatment of ascorbic acid produced the greatest amount of furan, followed by sucrose. The smallest amount of furan produced thermally was from glucose. At pH 7, autoclaving of glucose and fructose solution produced significantly ($P < 0.05$) more furan than sucrose and ascorbic acid. Thermal treatment of sucrose produced the least amount of furan. Compared to pH 7, significantly ($P < 0.05$) more furan was formed at pH 3 in fructose, sucrose, and ascorbic acid solutions, but less ($P < 0.05$) furan was produced in glucose solution. Our results suggest that pH of the solution is a major factor influencing the thermally induced formation of furan. Research conducted on the furan formation from solutions has to define pH. In the previous experiment (**Figure 5B**), when pHs of solutions were not adjusted, the pHs of sugar solutions were about 6.4 while the pH of ascorbic acid was about 3.0. Although the pHs of sugar solutions in the above experiments (**Figure 5B**) were similar to those of solution prepared in phosphate buffer (**Figure 6A**), much more furan was produced in sugar solutions prepared in sodium phosphate buffer. The results suggest that the phosphate dramatically increased the sensitivity (in terms of furan formation) of sugars in response to thermal treatment. The mechanism of the promotion by phosphate is under investigation.

We found the concentration of substrates affected furan formation. The amount of sugars is unlikely a limiting factor for the formation of furan in fruit and vegetables and their derived products since most of them contain at least 0.5% of individual sugars (*6*). However, the composition of sugars in food may also play a role as different sugars have varied potentials to form furan upon irradiation. For example, foods rich in fructose may produce more furan than those rich in glucose. There is also considerable variation in the levels of ascorbic acid in fruit juice. Orange juice contained much more ascorbic acid than apple juice. But the amount of furan formed from orange juice due to irradiation was less than that from apple juice (*5*) despite the higher amount of ascorbic acid. Therefore, other factors, such as concentration of antioxidants, may play an important role in the formation of furan in a given food.

Results showed that pH of solutions had significant effects on both heat- and radiation-induced formation of furan from sugars and ascorbic acid. Earlier studies have showed that pH influenced the formation of furan derivatives as a result of thermal treatment (*12*, *17*). It is unclear how pH affects the radiation-induced formation of furan from carbohydrates. The pH effect may be a consequence of protonation and deprotonation of various moieties of the carbohydrates. It is known that pH has an effect on stability of ascorbic acid. Under aerobic condition, ascorbic acid can be oxidized to dehydroascorbic acid, which undergoes further degradation. The rate of ascorbic acid oxidation increased as pH increased from 3 to 6, then reached a plateau when pH was above 6 (*18*). The pH−rate profile for the oxidative degradation of ascorbic acid appears to be different from that for the radiation-induced furan formation. Our results showed that, upon irradiation, much more furan was formed at low pH compared to neutral pH, and dehydroascorbic acid produced much less furan than ascorbic acid. This suggests the lower amount of furan formation at neutral pH is probably due to, in part, the higher rate in the conversion of ascorbic acid to dehydroascorbic acid at neutral pHs. Locas and Yaylayan (*9*) found that, under nonoxidative conditions, ascorbic acid is a more efficient source of thermally induced furan than dehydroascorbic acid. It appears that ascorbic acid is more sensitive to both thermal and irradiation processing than dehydroascorbic acid in terms of furan formation. Ascorbic acid is a weak acid. In aqueous solution, ascorbic acid can exist in at least two forms: undissociated acid (acidic) and conjugate base (ionic) (*19*). Acidic conditions favor formation of the undissociated form. Our results show that more furan was formed as a result of irradiation at low pH, suggesting the undissociated form of ascorbic acid is more susceptible to radiation. The pH effect on thermally induced furan varied depending on the type of substrates. For most of the substrates (fructose, sucrose, and ascorbic acid), lower pH increased furan formation.

Irradiation exerts its effect in aqueous solutions through free radicals generated from radiolysis of water (*11*). These free radicals include hydrated electron, hydroxyl radical, and hydrogen atoms. Ascorbic acid is an antioxidant that readily reacts with the free radicals such as the hydrated electron. As a result, ascorbic acid is converted to dehydroascorbic acid (*20*, *21*). The formation of dehydroascorbic acid from ascorbic acid by irradiation as well as the destruction of furan by irradiation (*5*) may prevent excessive accumulation of furan during irradiation of ascorbic acid.

Ascorbic acid and carbohydrates are also commonly used as additives in ready-to-eat meat products. The results of this study can be used for better formulation to minimize the production of furan due to thermal or irradiation processing. For example, if carbohydrates are required in formulation, glucose would be a better choice than fructose and sucrose to reduce the accumulation of furan due to irradiation. Unlike thermal processing (*10*), irradiation did not induce furan formation from polyunsaturated fatty acids, such as linoleic acid (data not shown).

In summary, our results showed that irradiation and thermal treatments induced formation of furan from ascorbic acid, fructose, sucrose, and glucose. Little was formed from organic acids. Among the three sugars, glucose produced the least amount of furan. The concentration of the substrates and pH of solutions influenced the formation of furan. As pH increased from 3 to 8, the irradiation-induced furan was reduced. pH is the major factor influencing formation of furan due to not only irradiation but also thermal treatment. Compared to thermal treatment (sterilization), irradiation (5 kGy) of sugars and ascorbic acid produced similar amounts of furan.

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