

Foods for a Mission to Mars: Investigations of Low-Dose Gamma Radiation Effects

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Abstract

Food must be safe, nutritious, and acceptable throughout a long duration mission to maintain the health, well-being, and productivity of the astronauts. In addition to a developing a stable pre-packaged food supply, research is required to better understand the ability to convert edible biomass into safe, nutritious, and acceptable food products in a closed system with many restrictions (mass, volume, power, crew time, etc.). An understanding of how storage conditions encountered in a long-term space mission, such as elevated radiation, will impact food quality is also needed. The focus of this project was to contribute to the development of the highest quality food system possible for the duration of a mission, considering shelf-stable extended shelf-life foods, bulk ingredients, and crops to be grown in space. The impacts of space-relevant radiation doses on food, bulk ingredient, and select candidate crop quality and antioxidant capacity were determined. Interestingly, increasing gamma-radiation doses (0 to 1000 Gy) did not always increase dose-related effects in foods. Intermediate radiation doses (10 to 800Gy) often had significantly larger impact on the stability of bulk ingredient oils than higher (≥ 1000 Gy) radiation doses. Overall, most food, ingredient, and crop systems investigated showed no significant differences between control samples and those treated with 3 Gy of gamma radiation (the upper limit estimated for a mission to Mars). However, this does

not mean that all foods will be stable for 3-5 years, nor does it mean that foods are stable to space radiation comprising more than gamma rays.

Introduction

A primary goal for designing a food system for a long duration space mission beyond low Earth orbit is to provide the crew with an acceptable, nutritious, and safe food supply while, at the same time, minimizing volume, mass, power, and waste (Perchonok 2003). Food quality and stability are essential for the well-being of astronauts. For travel to Mars or beyond, a large self-sustaining food system is being considered in tandem with extending the shelf-life of prepackaged foods. A likely scenario for the food system is using a combination of prepackaged foods, bulk ingredients, and crops to provide a well-balanced diet (Perchonok 2003). Bulk and prepackaged food items may be sent to the surface ahead of or along with the crew to establish a short-term food system while housing is being established and crops are being grown. Once a base is established, a Martian-grown vegan diet could be the main source of food considering the distance and high costs of a continuous re-supply alternative and a mission objective of an enclosed bioregenerative habitat. Prepackaged foods, either sent along with the crew or processed on the Martian surface, will be used for the return trip to Earth.

For a mission to Mars, prepackaged and bulk foods will need a 3-5 year shelf-life (Perchonok 2003). There are currently three categories of available extended shelf-life processed food items utilized by astronauts in space: 1) thermally processed / irradiated, 2) bakery / natural / intermediate moisture, and 3) freeze-dried processed foods (Space Center 2003). Thermally processed/irradiated foods have a shelf-life of 3-5 years, and thermally processed foods may last up to 7 years if stored in ideal conditions (Space Center 2003). The shelf-life of natural foods (up to 3-5 years) and intermediate moisture foods (1 year) is often limited by moisture, light, oxygen, and browning reactions (Space Center 2003). The short shelf-life of fresh fruits and vegetables necessitates processing to extend shelf-life, but consumption of fresh crops grown during a mission could have nutritional and psychological advantages over a more limited processed-foods-only diet. Freeze-dried foods are reported to have a shelf-life of one year (Space Center 2003);

however, astronauts have noticed a loss of quality and acceptability of freeze-dried products after approximately 6 months (Perchonok 2003). Packaging and storage conditions significantly influence the shelf-life of all of these foods.

Elevated levels of radiation encountered on a mission to Mars may impact not only human health, but also the stability of the food. Radiation is one of the top three concerns for a Mars mission (Wald 2003). The proposed mission to Mars includes 6-8 months in transit each way as well as 600 days on the surface. This mission scenario is estimated to encounter radiation levels on the order of 1-3 sieverts (1Gy gamma radiation = 1Sv) (Eckart 1994), and unpredictable cosmic ray bursts have the potential to increase radiation exposure up to 50 Sv per event. Radiation is known to affect the nutritional content, stability, and shelf-life of foods, although reports vary on dose-related effects. At space-relevant radiation levels, radiation effects on foods, ingredients, and the candidate crops are not well understood. Additionally, radiation can be used as a processing technique to sterilize foods (NASA approved 44 kGy), and therefore understanding both low-dose and high-dose radiation effects on foods is important.

Prolonged exposure to elevated radiation may kill cells or damage DNA, inducing the formation of cancer in astronauts, despite overall relatively low levels (Pence and Yang 1999). Measures must be taken to protect, prevent, and counteract the oxidative effects of radiation-induced free radical species. Proven countermeasures to the deleterious effects of a high radiation environment include compounds such as: 1) α -tocopherol (vitamin E), a known in-vivo antioxidant which protects cells and tissues from radical effects; 2) ascorbic acid (vitamin C), a terminal biological antioxidant compound; and 3) β -carotene (vitamin A precursor), a free radical quenching molecule (Buettner and Jurkiewicz 1996; Handelman 1996; Niki 1996). Few studies concerned with supplemental amounts of these vitamins as protective measures have been published; however, a study by Gaziev et al. (1996) reported that a daily radioprotective supplement contained: 3 mg vitamin A as retinol acetate, 30 mg vitamin E as α -tocopherol, 150 mg vitamin C as ascorbic acid, 15 mg β -carotene, 75 mg rutin, and 0.2 mg folic acid. It is widely accepted that dietary antioxidants should be provided to astronauts; therefore, the stability of these compounds for the duration of the mission is important.

Objectives

Investigations of the effects of low-dose gamma radiation on foods focused on the following: 1) select macro- and micro- nutrients and quality traits of fresh strawberries, tomatoes, carrots, and apples; 2) select micronutrients and sensory evaluation of irradiated air dried and freeze dried strawberries, tomatoes, carrots, and apples; 3) peanut and soybean oils; 4) antioxidant supplements (vitamins C and E and beta-carotene); and 5) different cultivars of wheat.

Materials and Methods

Materials

Fresh strawberries (Diamante), tomatoes (Roma), carrots, and apples (Gala) and roasted peanuts were purchased from a local grocery store. Other cultivars of carrots (Bolero, Juwarrot, and Nutri red) and tomatoes (Persimmon, Black Prince, Dona, and Carmello) were grown in greenhouses and provided by Drs. Gioia Massa and Cary Mitchell from the Horticulture Department, Purdue University. Air-dried products were provided by FDP USA (Santa Rosa, CA). Freeze-dried products were provided by Van Drunen Farms (Momence, IL). Apogee and Perigee cultivars (called “space” wheat cultivars) were obtained from Dr. Bruce Bugbee at Utah State University and grown in greenhouses at Purdue. Triplicate samples of the following “terrestrial” wheat cultivars were purchased. Parshall, a hard red spring wheat, was obtained from Foundation Seed Company, Fargo, ND. Yecora Rojo and Yavaros 79, a hard red spring wheat and a durum wheat, respectively, were purchased from Foundation Seed Company (Davis, CA). A variety of dietary supplements were purchased from local grocery and health-food stores. Peanut and soybean oils were provided by Arista Industries, Inc. (Wilton, CT), Ventura Foods (Opelousas, LA), Archer Daniels Midland Company (Decatur, IL), and Bunge (Danville, IL). The chemicals utilized in this study were purchased from Sigma-Aldrich Chemical Co. (St. Louis, MO) and Fisher Scientific (Tustin, CA).

γ -Radiation Treatment

Samples were irradiated at select intervals from 0 – 10kGy at room temperature under normal atmospheric conditions using a Gammacell 220 ⁶⁰Co gamma irradiator (MDS Nordion, Ottawa, ON, Canada). The exposure rate was determined from the decay curve provided by the Purdue Radiological and Environmental Management and was ~10Gy/min. Gandolph (2006) verified differences in absorbed radiation doses following select radiation exposures using a Fricke dosimeter following the method described by Spinks and Woods (1990).

Methods

The methods utilized in this study were:

- Proximate analysis was conducted as follows. Moisture was measured based on the AOAC Official Method 925.45 (vacuum oven) (AOAC 2000). Ash was measured based on the AOAC Official Method 900.02B (furnace) (AOAC 2000). Protein content was determined using a FP-528 Protein/Nitrogen Determinator with Thermoelectric Cooler and Autoloader (LECO Corporation-St. Joseph, MI) following the method described by Nielsen (2003). Fat was measured based on the method described by Nielsen (2003) (Soxhlet Extraction). Carbohydrate was determined by difference (Nielsen 2003).
- Total Sugar was measured based on the method described by Pearson (1973) and Sullivan & Carpenter (1993) (Lane and Eynon Volumetric Process).
- Calcium, Magnesium, Sodium, and Potassium were measured based on the method described by Nielsen (2003). Samples were analyzed on a Perkin-Elmer Optima 4300 (MA, USA) inductively coupled argon plasma atomic emission spectrometer (ICP AES).
- Antioxidant Capacity was measured using TEAC (Kapasakalidis et al. 2006), FRAP (Benzie & Strain 1999), and/or DPPH (Miller et al. 2000) methods.
- Vitamin C was determined following the AOAC Official Method 967.21 (2,6 Dichloroindophenol Titrimetric Method) (AOAC 2000) and Nielsen (2003).
- Total Phenolics were measured based on the method described by Asami et al. (2003) (Folin Ciocalteu Procedure).

- Carotenoids (alpha- and beta- carotene and lycopene) were extracted based on the method described by Ferruzzi et al. (1998). Quantification of extracted sample was done by reverse-phase high performance liquid chromatography (HPLC) as described by Keane et al. (2007).
- SDS-PAGE was performed on proteins that were isolated from ground wheat flour using a method of Hamaker et al. (1995). The isolated proteins were run on a 10-20% Criterion gradient gel (Bio-Rad, Hercules, CA) at 200 V for 1 hour using a PowerPac HC (Bio-Rad, Hercules, CA). Gels were stained and destained to visualize protein sizes.
- Mixograph methods were adapted from AACC Method 54-40 (1995).
- Pasting curves were generated using a Rapid Viscoanalyzer with a rotating spindle (Grant 1998).
- To measure starch damage, a starch damage kit (Megazyme Starch Damage Kit, Wicklow, Ireland) was utilized that follows AACC Method 76-31 (1995).
- The 2-Thiobarbituric Acid reactive substances test measured lipid oxidation using a method adapted from Kulisic et al. (2004).
- Conjugated dienes in oil samples were measured using the IUPAC method 2.505 (1987).

Results and Discussion

Effects of Gamma Radiation on Select Fresh Fruits and Vegetables

There was generally no effect of γ -radiation (up to 10kGy) on the macronutrients, total antioxidant capacity, total phenolics, and alpha and beta carotenoids in fresh strawberries, tomatoes, carrots, and apples after 1 day of storage following irradiation. However, longer storage (3 days) following radiation treatment caused a significant decrease ($p < 0.05$) in the micronutrients at all radiation doses and also severe physical degradation (Figure 1). Ascorbic acid in fresh strawberries and tomatoes was degraded at radiation doses ≥ 10 kGy, but the ascorbic acid in carrots and apples was generally stable after 1 day following irradiation. It is hypothesized that the considerable alterations in the cell wall structures of the tomato and strawberry that occur during

ripening could contribute to the sensitivity to higher radiation doses observed in this study. Lycopene in fresh tomatoes was degraded at radiation doses $\geq 10\text{Gy}$ after 1 day following irradiation. Radiation dose, length of storage following radiation exposure, and type of produce all should be considered when designing a diet for quality and optimum micronutrient consumption.

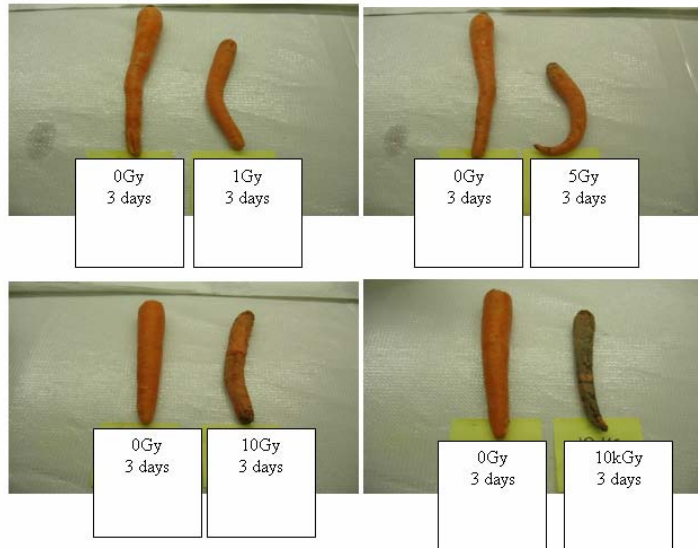


Figure 1. Photos of control and irradiated carrots and apples after 3 days of storage at room temperature following radiation treatment (0 – 10 kGy).

Effects of Gamma Radiation on Select Air-Dried and Freeze-Dried Fruits and Vegetables

The antioxidant capacity, ascorbic acid, phenolics, and carotenoids (alpha, beta, and lycopene) in air-dried tomatoes, carrots, and apples and in freeze-dried strawberries and apples were generally stable when exposed to γ -radiation up to 10kGy and stored at 25°C and 35°C for up to 6 months. In contrast to the nutrient stability, sensory panelists could differentiate (with a 95% confidence limit) samples stored at 35°C from samples stored at 25°C for 6 months. The sensory panelists most preferred the appearance of samples stored at 25°C and least preferred the samples stored at 35°C for 6 months due to the darker colors and browning observed in these products. Further study on the acceptability of shelf-stable products following radiation treatment and storage is recommended.

Effects of Gamma Radiation on Micronutrients in Carrot and Tomato Cultivars

The effects of γ -radiation (0Gy-10kGy) on the micronutrients of different carrot cultivars ('Bolero', 'Juwarrrot', and 'Nutri red') and tomato cultivars ('Persimmon', 'Black Prince', 'Dona', 'Carmello', and 'Roma') were similar. Ascorbic acid was generally stable in the carrot cultivars, but both ascorbic acid and lycopene in the tomato cultivars were significantly ($p < 0.05$) affected by increasing radiation exposure. Unlike the lycopene in tomatoes, the lycopene content in the 'Nutri red' carrot cultivar was not affected by radiation doses up to 10kGy. Again, the considerable alterations in the cell wall structures of the tomato during ripening could contribute to its sensitivity to higher radiation doses. Compositional differences between cultivars also merit attention when selecting crops to optimize a diet.

Effects of Gamma Radiation on Peanut and Soybean Oils

Peanut oil, intact peanuts, and soybean oil samples were treated with 0 to 1000Gy doses of gamma radiation, stored at 65°C (accelerated storage), and analyzed over a two-month period utilizing Conjugated Diene (CD) and 2-Thiobarbituric Acid Reactive Substances (TBARS) methods to track primary and secondary products of lipid oxidation, respectively. Effects of antioxidant addition (0.02% of tertiary butylated hydroquinone, TBHQ) and vacuum packaging on CD and TBARS levels in oils were determined. Oils

were extracted from intact peanuts following irradiation using a screw press (Taby Press, Taby Skeppsta, Orebro, Sweden), centrifuged at 5000xg for 10 min, and filtered using disposable 1µm glass fiber membranes (Acrodisc 25 mm syringe filters, Life Sciences, Frederick, CO) prior to analysis. Similar trends of oxidation, independent of radiation treatment, prevailed in both conjugated diene and TBARS analyses. Higher levels of oxidation were observed in soybean oil than in peanut oil. A higher percentage of linolenic acid (18:3n3) in soybean oil would account for a higher response in the TBARS assay because MDA is a decomposition product of linolenate (Frankel 1998). Linolenate is also a more readily oxidized substrate which may account for higher overall conjugated diene levels. At the elevated storage temperature, 65°C, increasing trends were observed in accordance with increasing radiation exposure up to 100 Gy in both conjugated diene and TBARS in soybean oils (Figures 2 and 3). Interestingly, a significant decrease in both conjugated diene and TBARS products in soybean oils was found between 100 and 1000 Gy. These trends with radiation dose were also found in peanut oils. Peanut oils extracted from intact peanuts that had been exposed to the radiation treatments showed lower levels of oxidation than the isolated peanut oils that received radiation treatment.

In both peanut oils and soybean oils stored in opened containers, time was the most significant factor in development of oxidation accounting for >84% of the variability in the data ((Type III SS/df)/MSE). The addition of countermeasures (vacuum packaging, 0.02% TBHQ, and both) significantly ($p<0.05$) delayed the onset time and maximum levels of oxidation. When countermeasures were used, radiation increasingly contributed to oxidation, along with storage time. For example, for vacuum packaged peanut oils, radiation dose accounted for 18% of TBARS and 82% of conjugated diene (CD) variability; while storage time accounted for 69% TBARS and 16% of CD variability ((Type III SS/df)/MSE). For vacuum packaged peanut oils containing TBHQ, radiation dose accounted for 43% of TBARS and 82% of CD variability; while storage time accounted for 39% TBARS and 16% of CD variability ((Type III SS/df)/MSE). Significant differences were found in the oxidation of oils from different companies and different lots from the same company, and oils to be used for an extended mission should be selected carefully. Radiation-induced changes in the lipid oxidation pathway warrant further investigation.

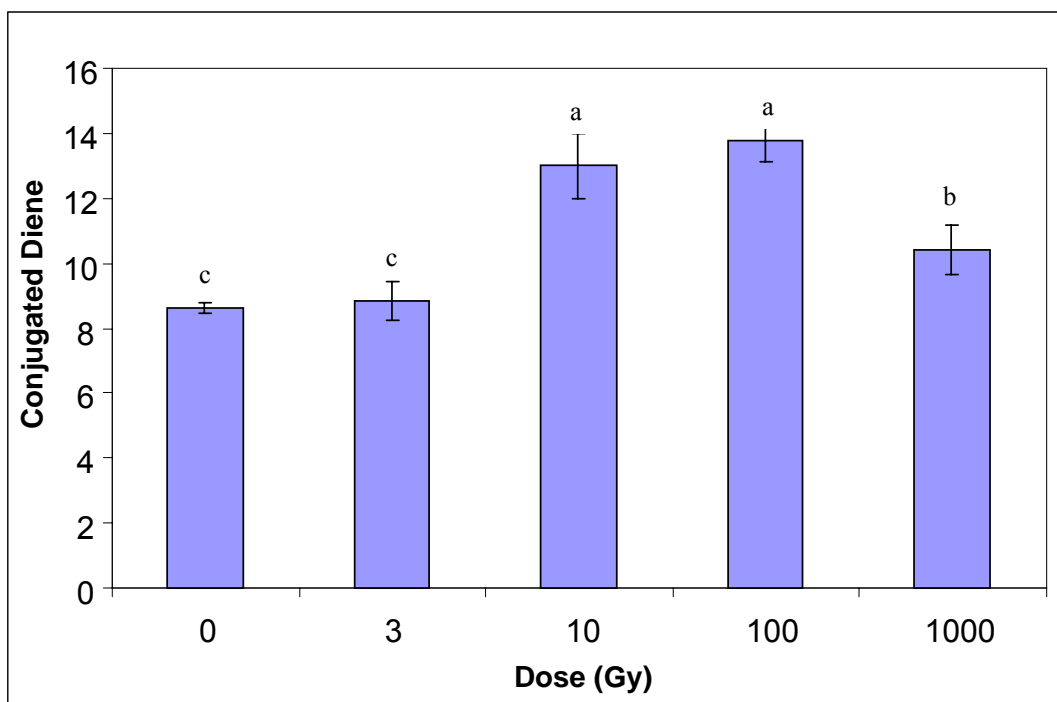


Figure 2. Conjugated diene values for soybean oil stored at 65°C for 21 days following gamma-radiation exposure (0 – 1000 Gy). Letters indicate significant difference ($\alpha=0.05$) determined using SAS Duncan's test statistic.

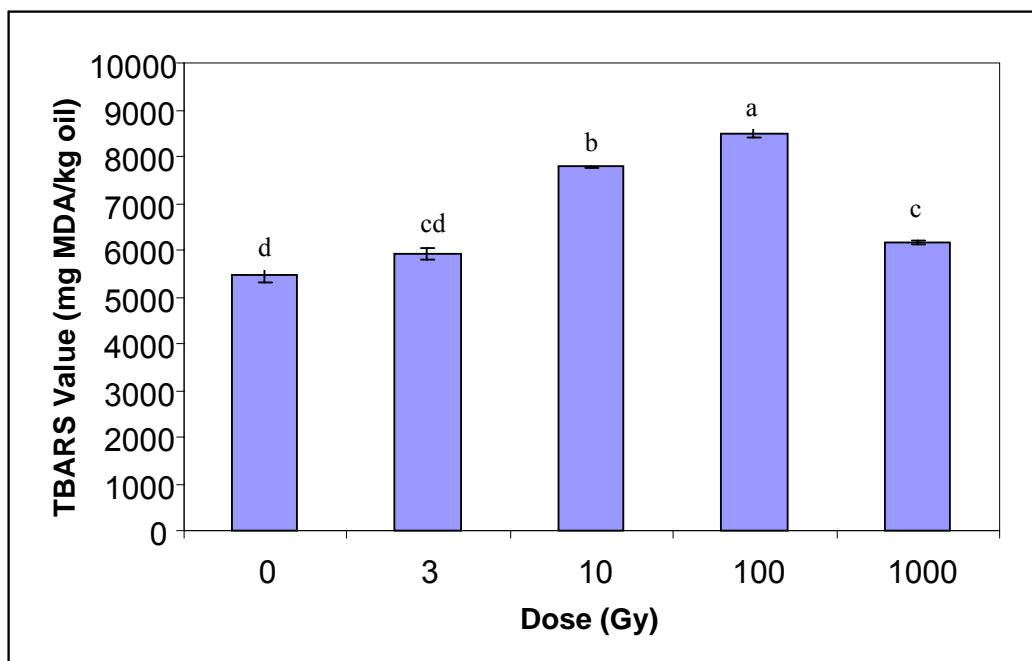


Figure 3. TBARS values for soybean oil stored at 65°C for 21 days following gamma-radiation exposure (0 – 1000 Gy). Letters indicate significant difference ($\alpha=0.05$) determined using SAS Duncan's test statistic.

Effects of Gamma Radiation on Vitamin C, Trolox, and β -Carotene

Dietary supplement antioxidants are proposed as a dietary countermeasure to maintain astronaut health in the extended elevated radiation environment of space travel. To assure stability of the antioxidants in the expected space storage conditions, it is important to study the effects of low-dose radiation on the antioxidants in the forms that may be used as supplements. The most common ingredient in supplements is vitamin C, which is present in 45% of supplements (Balluz et al., 2000). It is an essential micronutrient for humans as well as a powerful antioxidant. The effects of radiation and storage on vitamin C tablets, multivitamins containing vitamin C, and powdered ascorbic acid were determined. These supplements were irradiated from 0 to 1000 Gy, stored at room temperature in the dark, and analyzed over a three-month period utilizing FRAP (antioxidant capacity) and HPLC (vitamin C concentration) methods. No broad trends were found for the effects of either radiation or storage on vitamin C concentration or

antioxidant capacity. Therefore, it appears that vitamin C in dry supplement form may be stable to radiation at space relevant doses, although investigations into extended shelf-life applications are needed.

However, vitamin C in solution is much less stable than dry vitamin C supplements. Freshly prepared 500 μM solutions of ascorbic acid were irradiated at 0, 3, 10, 50, 100 Gy, the absorbance from the FRAP assay was monitored over a period of 48 hours, and endpoint absorbance values are shown in Figure 4. Significantly larger decreases in absorbance values were directly related to higher levels of radiation exposure. Data extrapolation using the linear regression from absorbance values for ascorbic acid solutions (500 μM) irradiated at 0, 3, 10, 50, and 100 Gy was used to predict the time it would take for ascorbic acid solutions to reach a zero-response point with the FRAP assay (Table 1). As radiation dose increased, the efficacy of ascorbic acid solutions to act as reducing agents decreased.

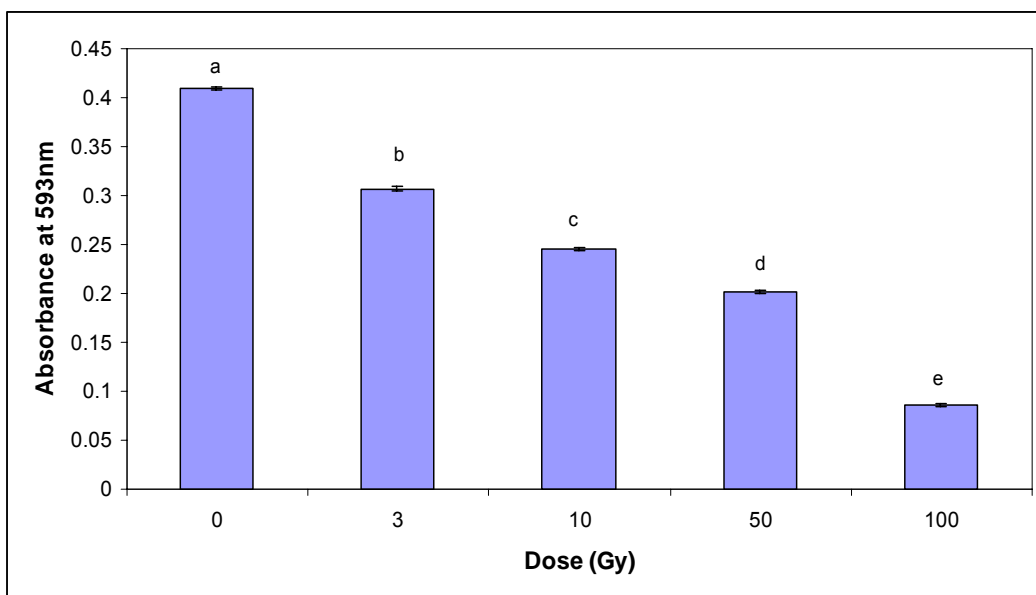


Figure 4. Absorbance values for ascorbic acid solutions (500 μM) exposed to select doses of γ -radiation, as measured by the FRAP assay after 48 hours of storage

Table 1. Predicted time until the reducing power of irradiated ascorbic acid solutions reached zero as measured by absorbance in the FRAP assay.

Radiation Dose (Gy)	Time to FRAP Extinction (hr)	Times Faster than control
0 (control)	159.8	--
3	98.7	1.62
10	82.4	1.94
50	74.4	2.15
100	54.7	2.92

Trolox is a water soluble analog of α -tocopherol which is the most radiation- labile of the fat soluble vitamins (Diehl 1990). Aqueous solutions of Trolox (500 μ M) and equimolar aqueous solutions of ascorbic acid (250 μ M) and Trolox (250 μ M) were irradiated at 0, 3, 10, and 100 Gy. Trolox samples were monitored over a 324 hour period using the FRAP assay (Figure 5). Significant reductions in the reducing power of Trolox were found at radiation exposure doses \geq 3 Gy. As radiation dose increased, the time that Trolox was available to participate as a reducing reagent in the FRAP system was reduced (FRAP extinction occurred in 400 hours for the control sample and decreased to 360 hours for the 100Gy treated sample). However, equimolar solutions of ascorbic acid/Trolox showed no significant differences in FRAP results for samples irradiated at 0, 3, and 10 Gy. Similar studies using β -carotene found no trends in FRAP results for 0 to 100Gy radiation treatments of 500 μ M β -carotene. Overall, γ -radiation had an effect on solutions of antioxidants at levels as low as 3 Gy. Differences found using the FRAP assay were also apparent between the different types of antioxidant compounds analyzed.

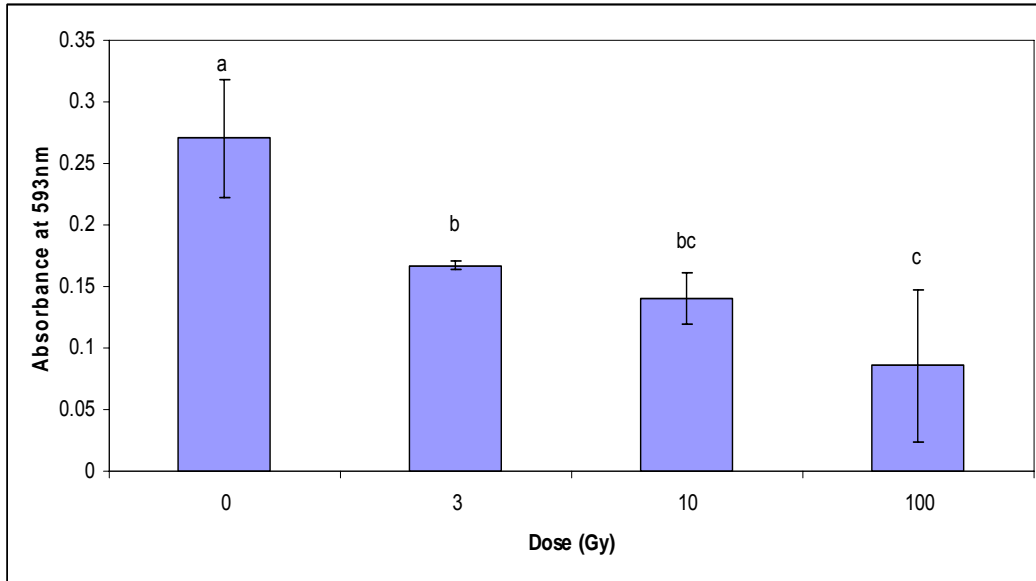


Figure 5. Absorbance values for Trolox solutions (500µM) exposed to select doses of γ -radiation, as measured by the FRAP assay after 324 hours of storage

Effects of Gamma Radiation on Wheat Cultivars

Apogee and Perigee are candidate wheat cultivars for an Advanced Life Support (ALS) system that are desirable due to their dwarf status and the reduced amount of inedible biomass produced (Bugbee et al., 1997ab; Bugbee, 1999). The effects of space-relevant radiation doses (1, 3, 10, 100 Gy) on the protein, fat, starch, and antioxidant capacity of these “space” wheat cultivars were compared to the same traits in “terrestrial” wheat cultivars (images of the wheat berries are shown in Figure 6).

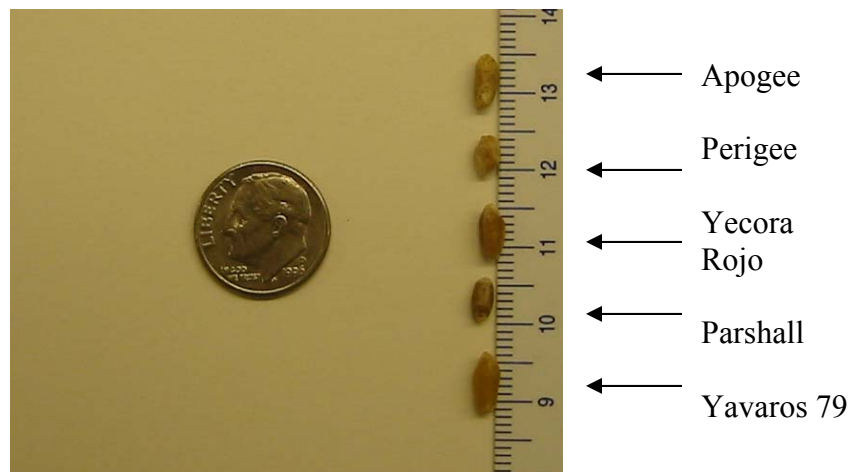


Figure 6. Visual Comparison of Wheat Berries from Various Wheat Cultivars

Perigee is the smallest and more spherical in shape than the other cultivars. Peak dough development time and SDS-PAGE analysis of Apogee and Perigee had conflicting indicators for bread quality, which may be explained by their high protein content (~18-20%). The lipid oxidation in Apogee and Perigee was significantly higher than in the other cultivars. The Apogee and Perigee cultivars had the highest crude ash contents, which seems to contribute more to lipid oxidation than total lipid concentration. Perigee was the only cultivar found to have a significant increase (~6%) in the amount of starch damage caused by milling, and pasting curve data support the finding that the starch granules in Perigee are structurally weaker than starch in the other studied cultivars. The antioxidant capacity in the Apogee and Perigee cultivars was significantly higher than in the terrestrial cultivars, which might be due to more bran in the varying surface area to volume ratios of the wheat berries studied.

Overall, Apogee is a more suitable candidate cultivar than Perigee to send to Mars due to its overall stability and nutritional properties. Apogee has a protein profile which indicates better dough properties as well as lipids and starches that were more resistant to degradation. The antioxidant capacity of this cultivar was the highest of those tested, which could be beneficial to astronauts in a high radiation environment.

Wheat gluten proteins are affected by radiation, as seen in fading protein bands in SDS-PAGE analyses with increased radiation exposure. Wheat exposed to 10Gy reached peak interaction strength in mixograph analyses more quickly than control samples in all the cultivars. Atomic force microscopy imaging revealed that gliadin exposed to 10 kGy denatured and increased the availability of the hydrophilic amino acids. Cultivars with high lipid and crude ash levels (Apogee, Perigee, and Parshall) were found to have the increasing lipid oxidation with increasing radiation exposure. All the cultivars had decreasing viscosity on pasting curves with increased radiation exposure. Trolox equivalence decreased as radiation levels increased, indicating a decrease in antioxidant capacity for all cultivars. In summary, radiation levels ≥ 100 Gy have a detrimental effect on the protein, starch, lipid, and antioxidant characteristics of wheat. However, no differences in the appearance, texture, or aroma of bread made from irradiated wheat (0 –

1000 Gy) were found by a sensory panel, and loaf volume may even be improved at 10 Gy (Figure 7).

An additional study addressed the effects of different radiation exposure protocols up to a total of 100Gy on the protein, starch, lipids, and antioxidant capacity in Yecora Rojo. Four radiation treatments were applied (1, 5, 10, and 20 exposures), all having a final total radiation exposure of 100 Gy, and results are presented in Table 2. SDS-PAGE and mixograph analyses were used to determine protein structure and functionality; a starch damage analysis kit and pasting curves were used to characterize starch structure and functionality; DPPH analysis determined antioxidant capacity; and a Thiobarbituric Acid Reactive Substances test was used to determine lipid oxidation. Analyses show significant differences between the peak dough development time, TEP equivalence, and Trolox equivalence in irradiated and non-irradiated samples ($P < 0.05$), but no differences with the various radiation treatments ($P > 0.05$). Therefore, the rate at which the wheat was exposed to radiation did not influence the structural and functional traits analyzed.

Table 2. Characterization Comparison of Yecora Rojo Exposed to 100 Gy in Varying Treatments

Total Radiation Dose (Gy)	Exposures	Peak Dough Development Time	TEP Equivalence (μM)	% Starch Damage	Trolox Equivalence (μM)
Control (0)	0	4:52 \pm 0:27a	0.92 \pm 0.09a	2.41 \pm 0.19a	11.43 \pm 1.04a
100	1	3:36 \pm 0:15b	1.16 \pm 0.08b	2.54 \pm 0.23a	9.12 \pm 0.92b
100	5	3:45 \pm 0:18b	1.13 \pm 0.10b	2.39 \pm 0.18a	9.26 \pm 0.87b
100	10	3:40 \pm 0:16b	1.24 \pm 0.12b	2.49 \pm 0.25a	9.02 \pm 0.89b
100	20	3:48 \pm 0:14b	1.11 \pm 0.17b	2.66 \pm 0.21a	8.83 \pm 0.93b

-TEP Equivalence – Measure of lipid oxidation

-Trolox Equivalence – Measure of antioxidant capacity in wheat

-Letters (a, b, c, d, e) next to values in the same column indicate values that are statistically different ($P < 0.05$)

Control

10 Gy

100 Gy

1,000 Gy



Figure 7. Image of Breads Made from Wheat Berries Exposed to 0-1000Gy Gamma Radiation. The bread formulation was adapted from Collister and Blake (2000), and all breads were made using the same conditions in a Breadman Automatic Bread Baker (Salton, Inc., Mount Prospect, IL)

Conclusions

Many attributes in foods may not be affected by the estimated radiation exposure of 1-3Sv (~1-3Gy) for a mission to Mars; however, it remains important to understand how space radiation, not just single radiation sources such as γ -radiation, impacts foods. Space-relevant γ -radiation doses did affect some dietary supplements (decreasing the antioxidant capacity of ascorbic acid and trolox solutions); increased primary and secondary products of lipid oxidation; impacted the color and texture of fresh strawberries, apples, tomatoes, and carrots; and perhaps increased the loaf volume of breads made from wheat berries exposed to 10Gy of γ -radiation. Adding common barriers to extend the shelf-life of lipids (removing oxygen, adding antioxidants) increased the relative contribution of radiation to the development of lipid oxidation. Further research is needed to understand how to optimize shelf-life, quality, and safety of foods for the needed 3-5 years for a mission to Mars; how to control the effects of radiation on foods; how space radiation and not just individual radiation sources impact foods; and how to integrate the stored and fresh food sub-systems with the other essential sub-systems for a successful extended mission in space.

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References

- AACC (1995). Official Methods of the AACC. Saint Paul, MN, American Association of Cereal Chemists.
- AOAC International. (2000). AOAC International 2000 Official Methods of Analysis. Seventeenth Edition.
- Asami, D., Hong, J.Y., Barrett, D., and Mitchell, A. (2003). "Comparison of the Total Phenolic and Ascorbic Acid Content of Freeze-Dried and Air-Dried Marionberry, Strawberry, and Corn Grown Using Conventional, Organic, and Sustainable Agricultural Practices." Journal of Agricultural and Food Chemistry. **51** (5):1237-1241.
- Balluz, L.S., Kieszak, S.M., Philen, R.M., and Mulinare, J. (2000). Vitamin and Mineral Supplement Use in the United States. Results from the Third National Health and Nutrition Examination Survey, Arch.Fam. Med. 9,258-262.
- Benzie, I. and J. Strain (1999). "Ferric Reducing / Antioxidant Power Assay: Direct Measure of Total Antioxidant Activity of Biological Fluids and Modified Version for Simultaneous Measurement of Total Antioxidant Power and Ascorbic Acid Concentration." Methods in Enzymology 299: 15-27.
- Buettner, G. R. and B. A. Jurkiewicz (1996). Chemistry and Biochemistry of Ascorbic Acid. Handbook of Antioxidants. L. Packer and E. Cadenas. New York, Marcel Dekker, Inc.: 91-115.

- Bugbee, B. 1999. Engineering Plants for Spaceflight Environments. American Soc. for Gravitational and Space Biology Bulletin. 12:67-74.
- Bugbee, B. and G. Koerner. 1997a. Yield Comparisons and Unique Characteristics of the Dwarf wheat cultivar "USU-Apogee". Adv. Space Res. 20:1891-1894.
- Bugbee, B., G. Koerner, R. Albrechtsen, W. Dewey, and S. Clawson. 1997b. Registration of USU-Apogee Wheat. Crop Science 37:626.
- Collister, L. and A. Blake (2000). The Bread Book. New York, NY, The Lyons Press
- Diehl, J. F. (1990). Safety of Irradiated Foods. New York, Marcel Dekker, Inc.
- Eckart, P. (1994). Life Support & Biospherics. Munchen, Germany, Herbert Utz Publishers.
- Ferruzzi, M.G., Sander, L., Rock, C.L., and Schwartz, S.J. (1998). "Carotenoid determination in biological microsamples using liquid chromatography with coulometric electrochemical detection". Analytical Biochemistry. **256**: 74-81.
- Frankel, E. N. (1998). Lipid Oxidation. Bridgwater, UK, The Oily Press LTD.
- Goins, G. D., N. C. Yorio, G. W. Stutte, R. M. Wheeler and J. C. Sager (2003). Baseline Environmental Testing of Candidate Salad Crops with Horticultural Approaches and Constraints Typical of Spaceflight. International Conference on Environmental Systems, Vancouver, B.C., Society of Automotive Engineers, Inc.
- Gandolph, J. (2006). Effects of Low Dose Gamma-Radiation on Select Lipids and Antioxidants. Department of Food Science. West Lafayette, Indiana, Purdue University. Masters.
- Gaziev, A.I., Sologub, G.R., et al. (1996). "Effect of vitamin-antioxidant micronutrients on the frequency of spontaneous and in vitro gamma-ray-induced micronuclei in lymphocytes of donors: the age factor." Carcinogenesis **17(3)**: 493-9.
- Grant, L. A. (1998). "Effects of starch isolation, drying, and grinding techniques on its gelatinization and retrogradation properties." Cereal Chemistry **75(5)**: 590-594.
- Hamaker, B. R., A. A. Mohamed, J. E. Habben, C. P. Huang and B. A. Larkins (1995). "Efficient procedure for extracting maize and sorghum kernel proteins reveals higher prolamin contents than the conventional method." Cereal Chemistry **72(6)**: 583-588.

- Handelman, G. J. (1996). Carotenoids as Scavengers of Active Oxygen Species. Handbook of Antioxidants. L. Packer and E. Cadenas. New York, Marcel Dekker, Inc.: 259-314.
- IUPAC (1987). Standard Methods for the Analysis of Oils, Fats, and Derivatives. Boston, Blackwell Scientific Publication, International Union of Pure and Applied Chemistry.
- Kapasakalidis, P.G., Rastall, R.A., et al. (2006). "Extraction of Polyphenols from Processed Black Currant (*Ribes nigrum* L.) Residues." Journal of Agriculture and Food Chemistry **54**: 4016-4021.
- Keane, E.G. et al. (2007). "Characterization of Carotenoids Pigments in Mature and Developing Kernels of Selected Yellow- Endosperm Sorghum Varieties." J. Agric. Food Chem. **55(7)**: 2619-2626.
- Kuliscic, T., A. Radonic, V. Katalinic and M. Milos (2004). "Use of different methods for testing antioxidative activity of oregano essential oil." Journal of Food Chemistry **85**: 633–640.
- Lane, H.W., Schoeller, D.A. et al. (1999). Nutrition in Spaceflight and Weightlessness Models, CRC Press LLC.
- Miller, H. E., F. Rigelhof, L. Marquart, A. Prakash and M. Kanter (2000). "Whole-Grain Products and Antioxidants." Cereal Foods World **45(2)**: 59-62.
- Nielson, S. (2003). Food Analysis. Third Edition. Kluwer Academic / Plenum Publishers.
- Niki, E. (1996). α -Tocopherol. Handbook of Antioxidants. L. Packer and E. Cadenas. New York, Marcel Dekker, Inc: 3-25.
- Pearson, D. (1973). Laboratory Techniques in Food Analysis. Butterworth, London.
- Pence, B. C. and T. C. Yang (1999). Antioxidants: Radiation and Stress. Nutrition in Spaceflight and Weightlessness Models. H. W. Lane and D. A. Schoeller. Boca Raton, CRC Press: 233-251.
- Perchonok, M. (2003). Advanced Food Technology Workshop Report - Volume I. Houston, National Aeronautics and Space Administration.

- Space Center, Lyndon B. Johnson. (2003). Space Food Systems Laboratory Shelf Life Analysis Operations Guideline. National Aeronautics and Space Administration Lyndon B. Johnson Space Center. Houston, Texas.
- Spinks, J.W.T. and Woods, R.J. (1990). An Introduction to Radiation Chemistry. New York, Wiley.
- Sullivan, D. and Carpenter, D. (1993). Methods of Analysis for Nutrition Labeling. AOAC International.