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Quality parameters of tomatoes submitted to different doses of gamma radiation

Parâmetros de qualidade de tomates submetidos a diferentes doses de radiação gama

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Abstract

Ionizing radiation can be used for different purposes in the food industry. In this study, the effect of irradiation doses (0, 0.5, 1.0 and 1.5 kGy) on the quality parameters of long life tomatoes (*Lycopersicon esculentum* Mill.), was evaluated during 4 storage periods (1, 7, 14 and 21 days). The different treatments were evaluated by analysing for colour, pH, total soluble solids (TSS), total titratable acidity (TTA), ratio (TSS/TTA), hardness, total lycopene and ascorbic acid contents, weight loss and maturation stage (O_2/CO_2 ratio) for all the storage periods. The tomato samples were irradiated in a Co^{60} irradiator and maintained at 22 °C ± 1 °C. The quality of the tomato fruits was influenced by the gamma radiation basically by making the fruits softer and not degrading the ascorbic acid and lycopene contents at the doses evaluated. The irradiation process used in the doses evaluated was promising with respect to maintaining the quality parameters of long life tomatoes.

Keywords: *Physicochemical analysis; Ionizing radiation; Food irradiation; Storage period; Lycopene; Tomato.*

Resumo

A radiação ionizante pode ser utilizada para diferentes fins na indústria alimentícia. Neste estudo, avaliou-se o efeito das doses de irradiação (0, 0,5, 1,0 e 1,5 kGy) nos parâmetros de qualidade nutricional de tomates longa vida (*Lycopersicon esculentum Mill.*), durante quatro períodos de armazenamento (1, 7, 14 e 21 dias). Os diferentes tratamentos foram avaliados por análises de cor, pH, teor de sólidos solúveis totais (SST), acidez titulável total (ATT), razão (SST/AT), firmeza/textura, teor total de licopeno e ácido ascórbico, perda de peso e fase de maturação (taxa de O_2/CO_2), em todos os períodos de armazenamento. As amostras de tomate foram irradiadas em irradiador de Co^{60} e mantidas a 22 °C ± 1 °C. A qualidade dos frutos foi influenciada pelo processo de irradiação, basicamente tornando os frutos mais macios e não degradando os parâmetros de ácido ascórbico e licopeno, nas doses propostas por este estudo. O processo de irradiação, nas doses avaliadas, é promissor na manutenção da qualidade dos tomates longa vida.

Palavras-chave: *Análise físico-química; Radiação ionizante; Irradiação de alimentos; Período de armazenamento; Licopeno, Tomate.*

1 Introduction

Tomato (*Lycopersicon esculentum* Mill.) is a fruit with great commercial importance, considered one of the most widely cultivated vegetables in the world (CAMARGO; CAMARGO FILHO, 2008) and Brazil is one of the largest producers according to the Food and Agriculture Organization (FAO, 2015). Brazilian production was 4.29 million tons in 2014 and was estimated at 3.46 million tons for 2015 (IBGE, 2015). The long life tomato cultivars have an extended shelf life because of drastic reductions in the degradation of the pericarp cells, and in the synthesis of ethylene and carotenoids (HERNER;

SINK, 1973; MUTSCHLER et al., 1992; DELLA VECCHIA; KOCH, 2000). The irradiation process can improve the quality of the tomatoes and maintain an extended shelf life, besides promoting a reduction in the microbial load and the disinfestation of pests (FARKAS; MOHÁCSI-FARKAS, 2011).

The consumption of tomatoes has been recommended due to their rich nutritional composition, consisting of vitamins, minerals, antioxidants, flavonoids, ascorbic acid and carotenoids such as lycopene, amongst others nutrients and it may also play a preventive role against non-communicable diseases (NCDs) and in reducing the risk of certain cancers (NGUYEN; SHUWARTZ, 1999; GEORGE et al., 2004). One of the major problems affecting the tomato crop is its short shelf life due to oxygen absorption resulting in physicochemical changes, with post-harvest losses of around 21% in the production chain and 25% to 40% in the horticultural sector (RINALDI et al., 2011). Food irradiation technology appears as an alternative to reduce losses and improve post-harvest handling, in addition to contributing to quality maintenance and food safety, with studies aiming to achieve the proposed goals without incurring significant change in the sensory and nutritional parameters (MOHÁCSI-FARKAS et al., 2014).

Previously cited alternative methods known as non-conventional or non-thermal methods, have begun to gain importance in food conservation studies, mainly aiming to reduce losses and obtain safe products with high quality (DIEHL, 2002; SOMMERS; FAN, 2006; THOW; PRIYADARSHI, 2013). Currently, producers and exporters seek technologies such as the food irradiation technique, for sanitary purposes and to increase the shelf life of vegetable products, with a view to expanding foreign markets by meeting international requirements concerning the environment and food security (PEROZZI, 2007; BUSTOS-GRIFFIN et al., 2015).

Ionizing radiation can be used for different purposes in the food industry, highlighting the inactivation of spoilage microorganisms and pathogens, increasing the shelf life of products, pest control and the inhibition of sprouting (FARKAS, 2006; SOMMERS; FAN, 2006; FOLLETT, 2007; DUVENHAGE et al., 2012). Ionizing radiation is that whose energy is greater than that of the energy binding the electrons of atoms, and can be emitted by the radioactive decay of unstable nuclei. It is widely used to improve the physical, chemical and biological properties of materials and commercial products (KIRCHER; BOWMAN, 1964). The main industrial sources are gamma ray (γ-ray) and X-ray irradiators and electron accelerators. The γ-ray irradiators are the most commonly used ones for commercial purposes and produce continuous radiation through the natural decay process of radioisotopes such as cobalt-60 (Co^{60}) and Cesium-137 (Cs^{137}) (HALL, 1994; PINO; GIOVEDI, 2005).

Each food product has its specific nutritional composition and hence a specific procedure should be developed to maintain the organoleptic properties and nutritional quality, ensuring that it can be used without risk to consumer health (IAEA, 1999; DIEHL, 2002). With the regulation of irradiation standards such as the phytosanitary process in agribusiness, the demand for irradiated food products will increase, since the quarantine restrictions can affect the economy of a country (MUMFORD, 2002). Therefore more research must be carried out focused on the nutritional and quality parameters of food products, aiming to determine the limits for radiation doses with respect to quality assurance and food security.

Although several studies have been published on food irradiation, very little information is available on the quality properties of different cultivars of tomatoes after γ-radiation treatment. This study aimed to verify the effects of different doses of γ-radiation on the quality parameters of long life tomatoes during 21 days of storage, aiming to determine viable doses that do not compromise the quality of the final product or offer risks to consumer health.

2 Material and methods

The study was carried out at the Agroindustry, Food and Nutrition Department of the "*Luiz de Queiroz*" College of Agriculture (ESALQ/USP), located in Piracicaba-SP, Brazil. The irradiation tests were carried out at the Nuclear and Energy Research Institute (IPEN).

2.1 Raw material

Long life tomatoes produced by conventional cultivation were purchased in the green ripening stage at the local market in Piracicaba city, São Paulo state, Brazil. The maturity stage of the tomatoes was visually assessed using the criteria adopted by the USDA (CATALYTIC GENERATORS, 1994). Sample preparation was carried out on the same day samples were taken and radiation processing was carried out 24 hours after preparation. The fruits were immersed in a 0.5% NaOCl solution for ten minutes for surface decontamination in the pre-irradiation storage step, and stored for 24 h at 25 °C ± 1 °C and 60% ± 10% RH in fruit boxes ideal for irradiation (cartons with a capacity for 5 to 6 kg and dimensions of 365 cm × 275 cm × 135 cm).

2.2 Irradiation process

The source of gamma radiation was that available at IPEN with an activity of 11.1 PBq ($3x10^5$ Ci). The dosing of each batch of irradiated fruit was carried out following the Gafchromic® dosimetric system – Gammachrome YR Dosimeter Batch 5, Harwell Laboratory (IAEA, 2004). The dose rate was 3.2 kGy/h and the distance between the samples and the source of radiation was 20 cm. All samples were transported to the radiation facility and back to the laboratory in cartons and stored in a controlled environment room at 23 °C ± 1 °C. The tomatoes were submitted to different irradiation doses: T1= control (0 kGy); T2= 0.5 kGy; T3= 1.0 kGy; and T4= 1.5 kGy, and analysed for four periods (1, 7, 14 and 21 days).

2.3 Physicochemical analyses

Fruit boxes with irradiated tomatoes were stored in a controlled environment room at 22 °C ± 1 °C and 60% ± 10% RH. The fruits were chosen at random for analysis amongst those which were suitable for consumption. The physicochemical analyses were carried out for all treatments for the four periods. The parameters analysed were: light transmittance analysis of the pulp (colour), pH, total soluble solids (TSS), total titratable acidity (TTA), ratio (SST/TA), texture, analysis of the carotenoids (total and lycopene), ascorbic acid, weight loss and maturation stage (O_2/CO_2 ratio).

2.3.1 Colour

The colour of the tomatoes was measured using a Minolta colorimeter (Colour Meter 200b) measuring L*, a*, b*, Hue and Chroma, where L* represents the lightness, the Hue angle is the tone and Chroma indicates the chromaticity or colour purity. The CIE coordinates L*, a*, b* (Illuminant A) were measured and used to calculate the Chroma value (C*) = [(a* 2 + b* 2) 1/2], and the hue angle (h*) = tan-1 (b*/a*) (KONICA MINOLTA, 1998). The fruits were evaluated at nine different points and the means used for the statistical analyses.

2.3.2 pH

The pH was measured using a Tecnal model Tec-3MP pH meter using samples diluted ten times (10:100), according to Horwitz (2005). The evaluation was carried out in triplicate and the mean values used for the statistical analysis.

2.3.3 Total Soluble Solids (TSS)

The total soluble solids were quantified using a portable digital refractometer (Kruss model DR201-95). The results were expressed in °Brix according to Horwitz (2005).

2.3.4 Total Titratable Acidity (TTA)

The total titratable acidity was determined using a 0.1 M NaOH solution titrating samples diluted ten times (10:100) according to Horwitz (2005). The results were expressed in g of citric acid per 100 g of sample.

2.3.5 Ratio (TSS/TTA)

The TSS/TTA ratio was calculated from the ratio of the total soluble solids (TSS) to the total titratable acidity (TTA).

2.3.6 Hardness

Instrumental hardness was measured using a Stable Micro Systems texturometer model TA-TX2i with a 2 mm cylindrical *probe* which determined the result of the resistance in relation to the force applied by the device in Newtons (N). For the penetration test the *probe* was moved up and down at 1.0 mm s^{-1} to 10 mm after the breakdown voltage.

2.3.7 Lycopene

Lycopene was extracted and quantified according to the carotenoid methodology of Rodriguez-Amaya (2011) in an environment with poor lighting to avoid photo-oxidation of the pigments. The sample was diluted in cold acetone, vacuum filtered and macerated twice to extract the red colour from the matrix as much as possible. After extraction, petroleum ether was used to partition the carotenoids using a separating funnel, separating the acetone solution from the petroleum ether containing the pigment, which was transferred to a 25 mL volumetric flask. The absorbance of lycopene was read at 470 nm in a visible/UV spectrophotometer (Spectrophotomer Model I JK-UVS-752N), and the lycopene content calculated using the Equation 1 below:

$$Lycopene(\mu g/g) = \left(\left(A * y * 10^6\right) / A^{1\%}{}_{1cm} * 100\right) / m \qquad (1)$$

where: A = wavelength in nm; y = solution volume in mL; $A^{1\%}_{1cm}$ = carotenoid absorption coefficient; m = sample weight in g.

2.3.8 Ascorbic acid

Ascorbic acid was determined using the Tillmans titrimetric method as modified by Benassi and Antunes (1998), which is based on the reduction of 2,6-dichlorophenol-indophenol (DCPIP) by ascorbic acid. 10 g of tomato were placed in a conical flask containing 50 mL of 1% oxalic acid. The contents were filtered into a 25 mL flask, completed to volume with oxalic acid, and 10 mL titrated with a 0.2% solution of 2,6-dichlorophenol-indophenol until the appearance of a pink colour which was stable for 15 seconds. The results were expressed in milligrams of ascorbic acid per 100 grams of sample (mg 100 g^{-1}).

2.3.9 Weight loss

The packages with the fruits were weighed on a semi-analytical balance and the results obtained from the difference between the initial weight on the day of the experiment and the weight at the time of sampling, and expressed as the percentage of fresh weight loss.

2.3.10 O_2/CO_2 measurement

This was determined from the amount of CO_2 produced by the tomatoes in hermetically sealed plastic packages. Three tomatoes were placer in each package in triplicate. A Check Mate O_2 and CO_2, PBI Dansensor gas analyser was used for the analysis and the results expressed in mL kg^{-1} h^{-1}.

2.4 Statistical analysis

An experimental design with randomized blocks was used with three replicates per treatment, four doses/treatment and four storage times. The data obtained in the physicochemical determinations were submitted to an analysis of variance, and the means compared by the Tukey Y honestly significant difference (HSD) test (α= 0.05). The analyses were carried out using the statistical program SAS 9.3 (SAS, 2003).

3 Results and discussion

3.1 Colour

The tomatoes were initially in the green ripe stage, as reflected in the colour parameters after the irradiation process and storage. Regarding luminosity (L*), a parameter which goes from 0 to 100 (where 0 is black and 100 is white) and indicates brightness, the results for all radiation doses were higher in the first period (day 1) for all treatments, differing in comparison with the last storage period ($p < 0.05$) (Table 1).

Considering the storage period, a decrease in brightness was observed for the last period (day 21), regardless of the treatment, the tomatoes darkening with storage time. The control treatment was brighter at the beginning of storage, differing from the other treatments, while the dose of 1.5 kGy showed the lowest values on the first day, only not differing from the radiation dose of 1.0 kGy. The last storage day of the control treatment showed the highest values, the doses of 1.0 kGy and 1.5 kGy not differing from each other (Table 1).

Regarding the parameter a*, which measures the tomato colour from green to red, the results for all radiation doses in the first period (day 1) were lower than the other periods analysed, showing that tomatoes, regardless of the dose at the beginning, were redder at the end due to maturation and subsequent senescence. A significant difference ($p < 0.05$) was observed between the first and last period analysed, with the highest value for a* observed in the third period (day 14) and second period for the treatment with a radiation dose of 1.5 kGy and for the control treatment (0 kGy), respectively. For the doses of 0.5 and 1.0 kGy the highest values for a* were observed in the fourth period (day 21).On the first day of storage the dose of 1.0 kGy showed higher values, differing from the other treatments, indicating that the tomatoes were redder and probably at a more advanced maturity stage. At the end of the storage period, the dose of 0.5 kGy showed the highest results, because this treatment preserved the colour, differing from the other treatments, and the dose

Table 1. Colour parameters (L*, a*, b*, Hue and Chroma) of the treated tomatoes (0, 0.5, 1.0 and 1.5 kGy) for the four storage periods (1, 7, 14 and 21 days).

Dose (kGy)	Storage Period (days)	L*	a*	b*	Hue	Chroma
0.0	1	48.22 ± 0.57 a	6.73 ± 1.55 b	30.60 ± 0.86 a	77.25 ± 1.42 a	35.69 ± 0.68 a
	7	39.80 ± 0.16 b	25.99 ± 0.40 a	23.78 ± 0.64 c	47.47 ± 1.28 b	34.42 ± 0.31 a
	14	39.64 ± 0.40 b	24.44 ± 0.14 a	25.08 ± 0.22 c	46.62 ± 0.44 b	34.92 ± 0.07 a
	21	39.59 ± 0.07 b	24.52 ± 0.38 a	27.23 ± 0.26 b	47.34 ± 0.41 b	36.73 ± 0.37 a
0.5	1	46.67 ± 0.36 a	11.64 ± 0.20 c	30.94 ± 1.48 a	66.44 ± 1.05 a	32.28 ± 1.23 a
	7	40.52 ± 0.07 bc	25.42 ± 0.09 b	25.62 ± 0.21 b	43.86 ± 0.86 c	33.33 ± 0.30 a
	14	39.74 ± 0.36 c	25.27 ± 0.30 b	25.66 ± 0.23 b	46.26 ± 0.74 c	33.53 ± 0.88 a
	21	41.34 ± 0.57 b	28.32 ± 1.19 a	25.67 ± 0.31 b	50.09 ± 0.46 b	33.24 ± 0.42 a
1.0	1	45.87 ± 0.62 a	17.56 ± 1.65 b	28.70 ± 0.38 a	57.54 ± 2.19 a	32.43 ± 2.42 a
	7	42.56 ± 0.23 b	22.17 ± 0.36 a	26.59 ± 0.37 b	48.84 ± 0.01 b	33.25 ± 0.41 a
	14	40.65 ± 0.49 bc	22.56 ± 0.41 a	28.44 ± 0.45 ab	48.09 ± 0.71 b	33.25 ± 0.44 a
	21	40.43 ± 0.48 c	23.75 ± 0.45 a	28.27 ± 0.99 ab	50.75 ± 0.55 b	32.41 ± 0.86 a
1.5	1	45.31 ± 0.35 a	7.85 ± 0.55 c	25.87 ± 1.10 a	72.16 ± 0.81 a	29.33 ± 1.01 b
	7	41.18 ± 0.14 b	22.69 ± 0.14 b	25.73 ± 0.23 a	46.04 ± 0.20 b	35.79 ± 0,15 a
	14	41.04 ± 0.17 b	25.18 ± 0.51 a	27.18 ± 0.07 a	46.71 ± 0.57 b	37.76 ± 0.03 a
	21	40.93 ± 0.86 b	24.07 ± 0.35 ab	26.84 ± 0.20 a	47.40 ± 0.83 b	36.70 ± 0.67 a

Different letters in vertical columns for each dose differ significantly (p <0.05). Average of triplicate ± Standard Deviation.

of 1.0 kGy presented the lowest value, only differing from the dose of 0.5 kGy (Table 1).

Considering the colour parameter b*, the variable that measures the tomato colour from yellow to blue, the values were higher at the beginning, except for the treatment with 1.5 kGy, in comparison to the other periods. Tomatoes irradiated with a dose of 0.5 kGy presented higher results initially, but did not differ from the control treatment, while the dose of 1.5 kGy presented the lowest result, differing only from the dose of 0.5 kGy. At the end, the dose of 1.0 kGy showed the highest values, only differing from the dose of 0.5 kGy (Table 1).

The Hue angle was calculated from the parameters of a* and b*, indicating the shade, and also the value for Chroma (chromaticity) which measures the saturation or colour purity. The Hue angle together with the other colour parameters, help us to informally determine the ripeness stage of fruits and vegetables. In this study, it can be seen the Hue angle showed higher values at the beginning, regardless of the treatment. Higher values for the Hue angle show a greener tomato fruit, and the lower values for the Hue angle indicate increases in the maturation stage.

Regarding the periods, there was a decrease with storage time for all treatments. Significant differences were observed between the treatments at the beginning of storage, the control treatment presenting the highest value, while the dose of 1.0 kGy presented the lowest one, indicating a more advanced stage of maturation (Table 1).

The parameter Chroma showed that the samples were less saturated in the last storage period, with lower values for Chroma values. A non-significant increase in the Chroma value was observed during the storage periods for all treatments, except for the dose of 1.5 kGy, which showed a significant increase from the first to the second periods. With respect to the treatments, the control treatment achieved the highest values from the beginning up to the last storage period (Table 1).

The results presented for the colour parameters (L*, a*, b*, Hue angle and Chroma) indicated that tomatoes were greener initially, becoming reddish, saturated and less bright with time, showing that, depending on the treatment used, the fruit quality was affected to a greater or lesser degree of significance regarding the changes in colour. Helyes et al. (2006) showed that the colour parameters were closely correlated with the degree of maturity of tomato fruits. Castricini et al. (2004) observed greater colour retention when analysing tomatoes of the cultivar 'Deborah Plus' irradiated with doses of 0.25 and 0.5 kGy. However, these authors noted that the dose of 1.0 kGy resulted in intensely red coloured tomatoes. However, Fabbri (2009) showed that lower doses were more effective for the fruit colour and that the highest dose showed colour values equal to those of the control treatment (non-irradiated tomatoes).

3.2 pH value

The pH values of the tomatoes were more influenced by the doses of 1.0 kGy and 1.5 kGy, differing from the other treatments ($p < 0.05$) and showing the highest values at the end of the 21 days (Table 2). The pH values increased

Table 2. Hardness, Total Soluble Solids (TSS), pH, Titratable Acidity (TA) and Ratio (TSS/TA) of the tomatoes (0, 0.5, 1.0 and 1.5 kGy) during the four storage periods (1, 7, 14 and 21 days).

Dose (kGy)	Storage Period (days)	Hardness	Total Soluble Solids	pH	Titratable Acidity	Ratio
0.0	1	1.68 ± 0.03 a	3.40 ± 0.20 a	4.36 ± 0.00 b	0.47 ± 0.02 a	7.23 ± 0.61 a
	7	*	2.17 ± 0.15 b	4.40 ± 0.06 ab	0.38 ± 0.02 b	5.63 ± 0.17 b
	14	1.08 ± 0.16 b	2.50 ± 0.10 b	4.48 ± 0.00 a	0.37 ± 0.01 b	6.72 ± 0.23 ab
	21	0.72 ± 0.13 b	3.10 ± 0.10 a	4.45 ± 0.04 ab	0.39 ± 0.01 b	8.06 ± 0.45 a
0.5	1	0.83 ± 0.08 a	4.13 ± 0.15 a	4.38 ± 0.05 b	0.40 ± 0.03 a	9.88 ± 0.52 a
	7	*	2.10 ± 0.10 bc	4.41 ± 0.01 b	0.39 ± 0.02 ab	5.42 ± 0.18 c
	14	0.92 ± 0.08 a	2.03 ± 0.15 c	4.54 ± 0.00 a	0.34 ± 0.01 b	5.93 ± 0.49 c
	21	0.52 ± 0.13 a	2.50 ± 0.10 b	4.45 ± 0.02 ab	0.33 ± 0.00 b	7.61 ± 0.21 b
1.0	1	1.32 ± 0.21 a	2.70 ± 0.10 a	4.40 ± 0.08 b	0.39 ± 0.02 a	6.95 ± 0.50 ab
	7	*	2.23 ± 0.06 b	4.50 ± 0.02 b	0.36 ± 0.01 a	6.16 ± 0.06 b
	14	1.10 ± 0.30 a	2.30 ± 0.10 ab	4.62 ± 0.03 a	0.32 ± 0.00 b	7.25 ± 0.41 ab
	21	0.75 ± 0.10 b	2.20 ± 0.20 b	4.56 ± 0.02 ab	0.29 ± 0.00 b	7.70 ± 0.80 a
1.5	1	0.85 ± 0.13 ab	4.17 ± 0.06 a	4.29 ± 0.02 c	0.41 ± 0.01 a	10.33 ± 0.25 a
	7	0.90 ± .09 a	4.43 ± 0.21 a	4.45 ± 0.02 b	0.41 ± 0.01 a	10.83 ± 0.64 a
	14	*	2.47 ± 0.06 b	4.56 ± 0.01 a	0.35 ± 0.01 b	6.98 ± 0.32 b
	21	0.22 ± 0.03 b	2.17 ± 0.21 b	4.58 ± 0.05 a	0.27 ± 0.01 c	8.13 ± 1.03 b

Different letters in vertical columns for the same dose differ significantly (p <0.05). Average of triplicate ± Standard Deviation; *Analysis lost due to equipment problem.

with storage time for all treatments and decreased slightly between 14 and 21 days, ranging from 4.36 to 4.48 in the control treatment; 4.37 to 4.54 with a radiation dose of 0.5 kGy; 4.40 to 4.61 with 1.0 kGy and 4.29 to 4.57 with 1.5 kGy. The control treatment presented less variation (4.36 to 4.44) and become less acid during the last storage period, as also the other treatments. Initially the most acid pH was observed for the treatment with 1.5 kGy (4.29), becoming less acid at the end of the evaluation period (4.57). The highest mean pH value was observed with 1.0 kGy, differing from the other treatments ($p < 0.05$) (Table 2).

The tomato is considered to be an acidic fruit, and the results found in this study coincide with those of Bleinroth (1995), who stated that the pH of red ripe tomatoes was around 4.6. Studies with tomatoes showed there was a slight increase in pH values with the maturing process, due to the fact that their ability to synthesize organic acids became less than the consumption of these substances in the maturation process of the fruits (FERREIRA, 2004). Tavares and Rodriguez-Amaya (1994) found pH values ranging from 4.4 to 4.6 in fresh Brazilian tomatoes of the cultivar 'Santa Cruz'. The mean pH values ranged from 4.41 to 4.61 in discarded raw tomato samples and from 4.32 to 4.50 in sterilized samples, in experiments carried out by Nunes and Mercadante (2004). In a study carried out by Gomes et al. (2004), the results showed there were no significant differences during the evaluation periods of 7 and 14 days for tomatoes irradiated with treatments of up to 3.0 kGy, but became significant during the later periods evaluated.

3.3 TSS, TTA and ratio

The TSS expressed as °Brix is the main component responsible for the fruit flavour. The TSS values decreased in the treatments of tomatoes submitted to gamma radiation and maintained their values in the control treatment during the evaluation period, ranging from 3.40 to 3.10 °Brix in the control treatment; 4.13 to 2.50 °Brix with 0.5 kGy; 2.70 to 2.20 °Brix with 1.0 kGy and from 4.16 to 2.16 °Brix with 1.5 kGy. Differences ($p < 0.05$) were detected between the treatments, with the highest value (3.30 °Brix) observed with the dose of 1.5 kGy (Table 2).

The soluble solids (SS) content depends on the tomato variety, having an important influence on the industrial yield in tomatoes as a raw material for processing (GIORDANO et al., 2000; SHIRAHIGE et al., 2010). Gomes et al. (2004) showed that none of the treatments had any influence on the behaviour of the SS content in tomatoes treated with doses from 0 to 3.0 kGy. The °Brix values were found to be from 3.8 to 4.0 for tomatoes samples in the study of Nunes and Mercadante (2004), and in the range from 3.8 to 4.6 in fresh tomatoes in the study of Tavares and Rodriguez-Amaya (1994). In turn, Abreu et al. (1997) determined a dose of around 0.6 kGy as a treatment to delay the ripening of tomatoes, detecting mean °Brix values of 3.5 and 4.1 °Brix in tomatoes irradiated with doses of 0.3 and 1.0 kGy, and 5.0 °Brix for non-irradiated tomatoes.

It was observed that the values for total titratable acidity (TTA) decreased between the initial storage periods and the last period for all treatments, with the highest value being detected in the control treatment (0.38), while the lowest value was observed with the dose of 1.5 kGy (0.26). Significant differences ($p < 0.05$) were detected between the treatments, with the highest mean value observed in the control treatment (0.40) and the lowest value for the dose of 1.0 kGy (0.33) (Table 2).

Due to oxidation, the organic acid content tends to reduce after ripening, with the loss being influenced by the temperature during storage (FENEMA, 1985; SONNENBERG, 1985). Unlike that observed here, the TA values remained constant for tomatoes submitted to different doses of gamma radiation and maintained at room temperature in the study developed by Castricini et al. (2002). Castricini et al. (2004) observed variations in the TA values in tomatoes irradiated at doses of 0.5 and 1.0 kGy, while the control tomatoes and tomatoes submitted to a dose of 0.25 kGy maintained their TA levels during the 22 days of evaluation.

The ratio represents that of the total soluble solids and to the total titratable acidity (SST/TTA) and is commonly used as an index for the ripening fruits. The results for ratio only decreased for the treatments with 0.5 kGy and 1.5 kGy during the study period. The ratio ranged from 7.22 to 8.05 in the control treatment; from 9.88 to 7.61 with 0.5 kGy; from 6.95 to 7.70 with a dose of 1.0 kGy and 10.33 to 8.13 with 1.5 kGy, with the highest mean value observed with 1.5 kGy (9.06), differing from the other treatments ($p < 0.05$). An increase in the ratio was observed for all treatments from 14 to 21 days of storage. The increase observed in the TSS/TTA ratio with a dose of 1.0 kGy and in the control treatment may indicate an improvement in the organoleptic characteristics of the tomatoes (Table 2).

According to Kader et al. (1978), high-quality fruits contain more than 3% of SS, 0.32% of TTA and a ratio greater than 10, indicating a good combination of sugar and acid. No ratio greater than 10 was observed for any treatment at the end of the storage period, only being observed for the first two periods (1 and 7) for the treatment with 1.5 kGy. In the sensory analysis, tomatoes endowed with high values for ratio are correlated with a mild flavour while low values are related to more acid flavours (ZAMBRANO et al., 1996).

3.4 Hardness

According to Chitarra and Chitarra (1990), in fruits hardness involves physical characteristics related to their deformation under the application of a force. The hardness parameter was only maintained during the study period in the treatment with 0.5 kGy. A greater loss of hardness was observed with doses of 1.0 kGy and 1.5 kGy. The radiation dose of 1.0 kGy differed from the other treatments ($p < 0.05$), with a higher mean value being observed for the control treatment (1.16 N) (Table 2). The decrease in fruit firmness can be explained by the degradation of starch in the cell wall, the conversion of sugars and the dissolution of pectin substances (CHITARRA; CHITARRA, 1990).

The use of radiation in plant products can lead to losses in texture and softening of the tissues, caused by degradation of the carbohydrates and pectin substances responsible for the hardness of the cell wall components (TUCKER; GRIERSON, 1982; URBAIN, 1996). On the other hand, in the study by Castricini et al. (2004), tomatoes submitted to doses of 0.25 and 0.5 kGy showed maintenance of their degree of hardness up to the 22nd day of storage when kept under refrigeration, corroborating the results found here.

In studies of other irradiated vegetable products, Oliveira et al. (2006) reported a decrease in the texture of non-irradiated and irradiated (300 Gy and 900 Gy) guava fruits, a dose of 600 Gy being more significant than the other doses. Mohácsi-Farkas et al. (2014) also observed statistically significant differences in the texture between non-irradiated and irradiated samples of sliced carrots.

According to Tucker and Grierson (1982) and Wrzodak and Adamicki (2007), the production of the enzyme that triggers the hydrolysis of pectin (polygalacturonase) and is responsible for fruit softening in long life cultivar tomatoes, can be almost completely suppressed by radiation treatment, depending on the dose.

3.5 Lycopene

The mean values for lycopene for the irradiation treatments differed significantly from the control treatment ($p < 0.05$). The values for lycopene were maintained for all treatments in the last period of evaluation, presenting a great increase (peak) after 7 and 14 days for the treatments with irradiation and decreasing thereafter, ranging from 39.86 to 40.72 µg g^{-1} with a dose of 0.5 kGy; from 29.16 to 48.58 µg g^{-1} with 1.0 kGy; from 18.60 to 75.50 µg g^{-1} with 1.5 kGy; and from 13.99 to 23.54 µg g^{-1} in the control treatment (Table 3).

Lycopene is the main carotenoid present in ripened tomato fruits, considered as one of the most efficient antioxidants in the donation of electrons to neutralize oxidant molecules (RAO; AGARWAL, 2000). According to Hart and Scott (1995), ripe tomatoes normally contain about 3 to 5 mg of lycopene per 100 g of fruit. Tomatoes with an intense red colour have average lycopene levels of around 31 µg/g (RODRIGUEZ-AMAYA, 2011).

The lycopene content varies between different cultivars and conditions and some authors have determined a good correlation between the lycopene content and the colour of the tomatoes, normally increasing as they reach

Table 3. Antioxidant components (Lycopene and Ascorbic Acid - AA) in the tomatoes (0, 0.5, 1.0 and 1.5 kGy) during the four storage periods (1, 7, 14 and 21 days).

Dose (kGy)	Storage Period (days)	Lycopene (µg g^{-1})	Ascorbic acid (mg 100 g^{-1})
0.0	1	14.51 ± 2.67 a	24.41 ± 0.04 a
	7	23.54 ± 1.15 a	22.24 ± 0.02 b
	14	14.00 ± 4.24 a	11.41 ± 0.01 c
	21	15.94 ± 10.30 a	6.30 ± 0.01 d
0.5	1	39.86 ± 2.64 a	24.41 ± 0.04 a
	7	28.50 ± 13.39 a	22.11 ± 0.02 b
	14	40.73 ± 22.30 a	11.34 ± 0.02 c
	21	17.35 ± 4.05 a	6.36 ± 0.01 d
1.0	1	29.46 ± 2.28 a	24.26 ± 0.02 a
	7	31.92 ± 7.78 a	22.26 ± 0.01 b
	14	48.58 ± 16.32 a	11.41 ± 0.01 c
	21	29.16 ± 2.43 a	6.39 ± 0.01 d
1.5	1	18.60 ± 3.37 b	24.12 ± 0.02 a
	7	75.50 ± 8.50 a	22.19 ± 0.04 b
	14	45.69 ± 11.05 b	11.39 ± 0.01 c
	21	21.51 ± 2.52 b	6.39 ± 0.01 d

Different letters in vertical columns for each dose differ significantly ($p < 0.05$). Average of triplicate ± Standard Deviation.

the red ripening stage (D'SOUZA et al., 1992; ARIAS et al., 2000; CARVALHO et al., 2005). In Finland, the lycopene concentration in tomatoes was analysed in the summer by Heinonen et al. (1989), showing values ranging from 38 to 66 μg g^{-1}, while in the autumn, the values were smaller, ranging from 26 to 31 μg g^{-1}. Yang et al. (1987) found a mean lycopene content of 26.1 μg g^{-1} in red ripe tomatoes; Tavares & Rodriguez-Amaya (1994) observed a mean value of 59.2 ± 21.8 μg g^{-1} and Nunes and Mercadante (2004) found a range from 28.4 to 93.5 μg g^{-1}.

The use of gamma radiation in tomatoes showed an accelerated process of carotenoid accumulation, indicating the possibility of extracting a larger amount of lycopene, due to changes in the chemical structure of the fruit (CASTRICINI et al., 2002). On the other hand, Kumar et al. (2014) showed the lowest mean lycopene contents in tomatoes irradiated with a dose of 1 kGy, and the untreated fruits showed a significant increase during the storage period as compared to irradiated fruits, different from that observed in the present study.

The trans-lycopene isomer is present at a concentration of 79% to 91% in the tomato and approx. 50% is in the form of the cis-lycopene isomer (CLINTON et al., 1996). The processing of tomatoes and derivatives may improve the bioavailability of the lycopene, such as heat processing which enables cell wall disruption in the fruits (WILLCOX et al., 2003). Dewanto et al. (2002) showed that heat processing increased the bio-accessibility of lycopene after 2 min (3.11 ± 0.04 mg of trans-lycopene per g of tomato), 15 min (5.45 ± 0.02 mg of trans-lycopene per g of tomato), and 30 min (5.32 ± 0.05 mg of trans-lycopene per g of tomato) of heating at 88 °C.

3.6 Ascorbic acid

The treatments differed significantly with respect to the ascorbic acid content of the tomatoes ($p < 0.05$), the control treatment showing the highest mean value (16.09 mg 100 g^{-1}), while the lowest value was observed with 1.5 kGy (16.02 mg 100 g^{-1}). The behaviour of the ascorbic acid content was similar for all treatments, decreasing in each evaluation period, with values ranging from 24.41 to 6.30 mg 100 g^{-1} in the control treatment; 24.41 to 6.36 mg 100 g^{-1} with a dose of 0.5 kGy; 24.25 to 6.39 mg 100 g^{-1} with 1.0 kGy and from 24.12 to 6.38 mg 100 g^{-1} with 1.5 kGy. In the last period, the treatments with 1.0 kGy (6.39 mg 100 g^{-1}) and 1.5 kGy (6.39 mg 100 g^{-1}) presented the higher ascorbic acid contents, while the control treatment presented the lowest concentration (6.30 mg 100 g^{-1}) (Table 3).

According to Thayer et al. (1991) ascorbic acid is sensitive to ionizing radiation. During ripening, oxidation of the acids occurs with a reduction in the ascorbic acid content (TUCKER, 1993) and irradiation oxidizes a portion of the ascorbic acid to dehydro-ascorbic acid, also decreasing the amount of ascorbic acid (DIEHL, 1990). Kilcast (1994) showed a reduction in vitamin levels due to the use of irradiation. Dewanto et al. (2002) observed losses of vitamin C after 2, 15 and 30 min of heating at 88 °C. Corroborating with these results, the effect of gamma irradiation on tomatoes at a dose of 1 kGy, promoted a slight decrease in the concentration of ascorbic acid, but no significant decrease in the organoleptic parameters of the fruits (MOHÁCSI-FARKAS et al., 2014).

The ascorbic acid concentration ranged between 14.6 and 21.7 mg 100 g^{-1} fresh weight of ripe tomato fruit in the study of Abushita et al. (2000), with no differences between cultivars either for fresh consumption or for processed fruit. Tomatoes maintained their levels of ascorbic acid for 20 days of storage when irradiated at a dose of 0.5 kGy, but the values showed fluctuations with doses of 1.0 kGy and 2.0 kGy in the study of Gomes et al. (2004). Castricini et al. (2004) observed a higher ascorbic acid content when the fruits were submitted to 0.50 kGy as compared to the treatment with a dose of 1.0 kGy.

3.7 Weight loss

During fruit storage the transpiration and respiration processes are the main causes of fresh weight loss. Weight loss implies a loss of product quality (BRACKMANN et al., 2007; KLUGE; MINAMI, 1997), and may be caused by the activity of polygalacturonase (PG), the enzyme which increases the permeability of the cell wall, thereby increasing transpiration (FERREIRA, 2004).It is seen therefore important to quantify this parameter to evaluate the quality of the product during storage.

In this study, an increase in weight was observed during the first period, regardless of the treatment, with a significant production of ethylene and increase in respiration, forming reserves and synthesizing compounds (Table 4). There was no significant difference between the treatments (p <0.005) (Table 4). In the second evaluation period, there was a significant increase in weight loss, regardless of the radiation dose, indicating that the tomato decreased its synthesis and increased consumption and respiration. In the third period, there was strong evidence of weight loss; however no difference was detected in comparison with the previous period, regardless of the treatment. The last period was also marked by an increase in weight loss, indicating senescence and a reduced respiration rate since the third storage period (Table 4).

Vieites (1998) evaluated the weight loss of the tomato cultivar 'Debora' in polyethylene containers and found a value of 8.36% after 21 days of storage under refrigeration. Castricini et al. (2002) found similar levels for fresh weight loss on the 12th day of storage for tomatoes submitted to different doses of γ-radiation and kept under refrigeration at 12 °C. Bleinroth (1981) noted that the rate of water loss in non-deteriorated vegetables is variable for each plant and should not exceed 10%.

Table 4. Weight loss of the tomatoes (0, 0.5, 1.0 and 1.5 kGy) during the four storage periods (1, 7, 14 and 21 days).

Dose (kGy)	Storage Period (days)	% Weight Loss
0.0	1	-1.10 ± 0.17 b
	7	15.55 ± 1.21 a
	14	14.32 ± 0.73 a
	21	10.90 ± 1.47 a
0.5	1	-1.33 ± 0.23 b
	7	14.19 ± 1.46 a
	14	13.97 ± 1.32 a
	21	10.90 ± 2.29 a
1.0	1	-1.11 ± 0.27 b
	7	16.10 ± 2.80 a
	14	16.00 ± 1.39 a
	21	11.69 ± 0.97 a
1.5	1	-1.11 ± 0.39 b
	7	17.43 ± 1.90 a
	14	16.62 ± 3.70 a
	21	13.84 ± 5.15 a

Different letters in vertical columns for the same dose differ significantly (*p* <0.05). Average of triplicate ± Standard Deviation.

Table 5. O_2 and CO_2 concentrations of the tomatoes (0, 0.5, 1.0 and 1.5 kGy) during the four storage periods (1, 7, 14 and 21 days).

Dose (kGy)	Storage Period (days)	O_2	CO_2
0.0	1	14.74 ± 1.60 b	0.54 ± 0.05 a
	7	14.58 ± 0.38 b	0.44 ± 0.05 b
	14	17.53 ± 0.74 a	0.30 ± 0.00 c
	21	17.17 ± 0.45 a	0.37 ± 0.06 bc
0.5	1	13.64 ± 0.21 b	0.52 ± 0.04 a
	7	13.28 ± 0.86 b	0.46 ± 0.05 ab
	14	16.32 ± 0.59 a	0.30 ± 0.00 b
	21	16.68 ± 0.30 a	0.40 ± 0.00 b
1.0	1	13.10 ± 1.07 b	0.50 ± 0.00 a
	7	12.12 ± 0.87 b	0.46 ± 0.05 ab
	14	15.36 ± 0.24 a	0.32 ± 0.04 b
	21	16.15 ± 0.40 a	0.38 ± 0.05 b
1.5	1	11.38 ± 0.43 b	0.50 ± 0.00 a
	7	12.04 ± 0.51 b	0.46 ± 0.05 a
	14	15.06 ± 0.61 a	0.36 ± 0.05 b
	21	15.90 ± 0.00 a	0.40 ± 0.00 ab

Different letters in vertical columns for the same dose differ significantly (*p* <0.05). Average of triplicate ± Standard Deviation.

3.8 O_2/CO_2 ratio

The tomato is a climacteric fruit which still breaths after harvesting, enabling it to be harvested in the ripe green stage, but with full physiological development. In the present study the percentage of O_2 and CO_2 was evaluated in polyethylene containers. At the beginning of the storage period (from the first to the second periods), independent of the treatment, it was observed that the tomato showed reduced respiration, since the maturation process began to decrease with senescence of the fruits. In the third period (14 days), a more significant reduction in respiration was found for all treatments, indicating the onset of fruit senescence (Table 5).

4 Conclusion

- The tomato fruit quality was influenced by the irradiation process basically making the fruits softer (decreasing hardness), but not affecting the other quality parameters, hence not impeding the implementation of irradiation;
- The ascorbic acid and lycopene contents were not degraded by the gamma radiation at the doses applied;
- The irradiation treatments differed from the control treatment in relation to the lycopene content;
- The radiation dose of 1.5 kGy was the treatment showing the highest values for the main bioactive compounds in tomatoes.

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