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Effect of gamma radiation on shelf life and quality of onion (*Allium cepa* L.)

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Abstract Results revealed that the irradiated onion bulbs showed minimal weight loss as compared to those of the non-radiated (control) bulbs. For instance, at 280 days after irradiation, the maximum weight loss (84.84%) was found in control, whereas the minimal weight loss (47.72%) was found in 100 Gy-irradiated onion bulbs. Most strikingly, sprouting was completely inhibited by irradiation treatments irrespective of doses, and only the non-radiated (control) bulbs were found to be sprouted (i.e. 0.11 and 89.05% sprouting at the 60 to 280 days after irradiation, respectively). The severity of rots was markedly reduced by the application of gamma radiation. At 280 days after irradiation, the highest percentage of rot (26.31) was found in non-radiated control bulbs, whereas the lowest rot percentage (14.69) was observed in those bulbs irradiated with 100 Gy. Optimal colour, texture, TSS and pH which were mostly maintained in the irradiated bulbs. Size of onion bulbs of untreated control was reduced by 16.14%. In contrast, the size of irradiated bulbs was reduced only 0.98-2.72%. The findings would greatly contribute to reduce enormous postharvest loss of onions and maintain their quality during long-term storage and marketing at ambient condition.

Keywords: Gamma radiation, Onion, Postharvest, Storage life, Sprout inhibition

Introduction

Onion is a widely-grown spice crop in the world. Onion ranks the 1st in terms of production among the spice crops grown in Bangladesh. During 2020-21, 2.3 million MT tons of onions were produced from 194 thousand ha of land (BBS, 2022). A considerable quantity of the produced onions is conventionally stored to fulfill the domestic demand during the lean season (May to October). However, according to DAM (2020), total national demand of onion in Bangladesh is 3.0 million MT, and the current production is 2.6 million MT of which 25-30% is lost at postharvest level. Therefore, net availability of onions in Bangladesh, is around 1.8-1.9 million MT, and the remaining 1.1 million MT i.e. one-third of the requirements is actually imported principally from India

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followed by China, Myanmar, Pakistan, Egypt and Turkey. In the year 2020, total cost of importing onions to Bangladesh was around 154 million USD (Tridge, 2020). Onions are generally stored conventionally at the farmers' and traders' place at ambient condition without controlling temperature and relative humidity due to lack of modern low temperature storage facility. Onions are perishable, and storage loss of this spice has been reported as 40-50% (Sharma *et al*., 2020). The causes of postharvest losses of onions are manifold including cuts, bruises, fungal infection, weight loss and consequent shrinkage and sprouting. Sharma *et al*. (2015) reported that the predominant factors of postharvest losses of onion bulbs are sprouting and rotting, which ultimately result in reduced storage life and quality. In Bangladesh, weight loss of onions mainly occurs during hot summer (May-July) due to prevailing high temperature, and higher levels of rots are evident in the rainy season (June-July) due to high humidity. Sprouting of stored onions is a major problem in terms of their shelf life and quality. Decreased temperature during September-October results in breakdown in bulb dormancy and initiation of sprouting. Benkeblia *et al.* (2002) reported that sprouting, rotting, transpiration, heat production and microbial spoilage of onion bulbs mainly occur due to catabolism when stored at ambient temperature (18-25 ^{o}C) and high relative humidity (>85%). Sharma *et al.* (2015) mentioned a number of factors that influence storability of onion bulbs. Firstly, the genetically controlled properties like dry matter, pungency, skin colour, number of adhering scales and dormancy period. Secondly, the pre-harvest factors, which include nutrient management, irrigation, time and methods of harvesting and insect and disease management. Thirdly, the postharvest factors which include methods and duration of curing, sorting, grading, packaging and storage environment. Therefore, there is a need to develop modern technology for bulk and long-term storage of onions to minimize postharvest loss and maintain optimal quality at ambient condition, especially for those countries with limited cold storage facilities. Recommended storage conditions comprising low temperature and high relative humidity, are required for controlling sprouting, rotting and transpiration to prolong shelf life of onions, especially in developed countries (Adamicki, 2005). Tripathi and Lawande (2019) reported two distinct storage temperature and relative humidity (RH) regimes for onion i.e. 0-2 ^{o}C & 70% RH and 25-30 ^{o}C & 70% RH. The second condition prevails in the tropical countries like Bangladesh which encourage more storage losses. Earlier, Brice *et al.* (1997) also reported that onion is stored under ambient conditions without maintaining recommended storage temperature and humidity in tropical regions as the low temperature storage facilities are rarely available. Sharma *et al*. (2015) examined the storage life and quality of onions under aerobic and anaerobic conditions at ambient temperature and found lower sugar content and bulb firmness during storage under anaerobic condition. Like many other developing countries, in Bangladesh, modern postharvest storage facilities, especially cold chain management, is absent for onions, and alternative methods of bulk storage of onions with prolonged shelf life warrant investigation. In this regard, application of radiation from gamma sources may be a potential postharvest treatment to check sprouting, rotting and transpiration, and thereby prolong shelf life. Sharma *et al.* (2020) reported that onions bulbs irradiated with gamma rays at 120 Gy minimized weight loss, rotting and sprouting, while maintained best quality for 3 months at ambient condition. A further study conducted by Sharma *et al*. (2022) revealed that overall acceptability of onion rings irradiated at 1.5 kGy obtained the highest scores irrespective of packaging treatment. The research concluded that perforated polypropylene packaging and a gamma irradiation at 1.5 kGy was found to be most suitable for maintaining shelf life of the minimally-processed onion rings. In another study, Tripathi and Lawande (2013) reported no sprouting in onions (dark red, light red, white and yellow colour) when gamma irradiated at 60 Gy and stored under ambient conditions for 6 months. Time of application of radiation is also important. Rezaee *et al*. (2013) reported that irradiation of tubers during dormancy period was found the most effective technology for sprout control. Irradiation treatments have been reported to show varying effects on biochemical properties of onions. Onion bulbs (var. Bellary Red) when irradiated at 128.04 Gy significantly increased total pyruvic acid content from 17 to 22 μ mol mL^{-1} along with better retention of texture and colour (Kallai *et al.,* 2015). Jabeen *et al.* (2004) reported that onion bulbs irradiated with 8 Kr had minimum weight loss (28.59%), decreased firmness and pungency; minimum rotting (6.3%) was observed at 6 and 8 Kr; and 4, 6 and 8 Kr showed no sprouting at all. A study with application of 5 radiation doses (0.1. 0.2. 0.3. 0.4. and 0.5 kGray) using cobalt-60 irradiator (Nor din) revealed that the non-irradiated samples were either deteriorated or grown while all the irradiated samples were not. Vitamin C decreased with the dose increase from 30.53 to 14.44 mg 100 g^{-1}. Irradiation was found very effective in prevention of spoilage, elongation of germination period and decrease of vitamin C concentration (Saleh, 2015). In contrast, Firouzi *et al.* (2021) reported that onions, irradiated by 200 Gy, were not damaged rather their nutritional properties were preserved and pathogenic microorganisms were eliminated. The process indicated that application of 200 Gy radiation does not endanger the health of food and consumers. Similar report was also published by Munir *et al.* (2017) who reported that 0.10 kGy was found optimum to enhance onion shelf life without any significant change in physiological and as well as its nutritional value. With the foregoing facts and figures, this is clear that, gamma irradiation improves storability of onions, and storage duration varies with doses, variety and time of application. Onion is the most important spice crop in Bangladesh, and the largest import spice item in Bangladesh. In developing countries like Bangladesh, exploitation of radiation technology is unnoticeable. Therefore, research was related to improve the shelf life and quality of onions through radiation technological investigation. The present study was undertaken to investigate the effect of different doses of gamma radiation on shelf life and quality of onion with a view to suggest a suitable dose for increasing shelf life without deteriorating quality.

Materials and methods

Experimental materials

A commercially important onion variety, namely Taherpuri, was used for conducting the present experiment. Experimental onion bulbs were sourced from a commercial supplier in Mymensingh, Bangladesh. The bulbs were graded, and medium size bulbs of 20-40 g weight and 20-40 mm diameter were used for the study. A total 75 kg cured and graded onion bulbs were used for setting up the experiment, of which 15 kg was used as control (0 Gy), whereas 60 kg onion bulbs were used for imposing 4 different doses of gamma irradiation (50, 100, 150 and 200 Gy).

Experimental location

The experiment was conducted at the Postharvest Laboratory, Horticulture Division, Bangladesh Institute of Nuclear Agriculture (BINA), Mymensingh. The experimental site falls within latitude 24°26′N and longitude 90°15′E at an elevation of 18 m above the sea level. The experiment was conducted during the period from July 2020 to April 2021. The experimental area (Mymensingh) was located under subtropical climate, which is characterized by heavy rainfall during the months of April to September and scanty rainfall during rest of the year. The annual average rainfall of the area is 2249 mm. The average temperature and humidity are 23-31 °C and 60% during summer (March to September) and 15-27 °C and 49% during winter (October-February).

Experimental treatments and design

Onion bulbs were treated with gamma irradiation (0, 50, 100, 150 and 200 Gy) through ^{60}Co gamma irradiator (CG-5000) located at Bangladesh

Institute of Nuclear Agriculture (BINA), Mymensingh (Figure 1A). BINA having the research mandate for peaceful use of nuclear technique in agricultural fields, an irradiation source of Gamma Chamber (CG-5000) for exposing experimental samples was commissioned by Board of Radiation and Isotope Technology (BRIT), Mumbai, India in 2013. The equipment are calibrated from time to time by the Bangladesh Atomic Energy Commission (BAEC) and Board of Radiation and Isotope Technology (BRIT) for ensuring the delivery of required dose of gamma radiation to the experimental samples. So, doses were automatically measured by PLC (Programmable Logic Controller) system. During irradiation, the onion bulbs were packed in polyethylene bags and placed in the irradiation chamber and exposed to gamma irradiation for different periods of time. The critical dose rate (CDR) at the time of irradiation was 2.69 KGy hr^{-1}. To estimate dose rate, 2.69 KGy hr^{-1} doses of ^{60}Co gamma irradiator was evaluated using Ceric-Cerous dosimeter. The absorbed dose of Ceric-Cerous (~3KGy) dosimeter was measured using an electrochemical potentiometer cell in millivolts (mV) ranges. The treatment periods were 1 min 7 s, 2 min 14 s, 3 min 21 s and 4 min 28 s for 50 Gy, 100 Gy, 150 Gy and 200 Gy dose of gamma irradiation, respectively. The non-irradiated onion bulbs were kept as control (0 Gy). The non-irradiated bulbs and irradiated bulbs were kept in ventilated plastic crates (5 kg each) at ambient condition (Figure 1 B, C). The experiment was laid out in completely randomized design (CRD) with three replications of 5 kg onion bulbs per replication) (Figure 1 B, C). The temperature and relative humidity of the storage room (Postharvest Lab, BINA) ranged from 20-30 ^{o}C and 56-89%, respectively during entire 10-month period of investigation (April 2020 to July 2021).

Figure 1. Application of gamma irradiation to the experimental onion bulbs using ^{60}Co gamma irradiator (CG-5000- A), and the irradiated onion bulbs held in rigid plastic crates and stored at ambient condition for observation (B and C)

Parameter investigation

Different postharvest physico-chemical properties (physiological weight loss, size, colour, texture, TSS and pH) and severity of rots and sprouting, were investigated up to 280 days of irradiation. Physiological loss in weight (%), rotting (%) and sprouting (%) were observed at every 20-day interval up to 280 days. The total soluble solids (^{o}Brix) and pH were evaluated at 30-day interval up to 200 days. Size, colour and texture of the onion bulbs subjected to irradiation treatments were evaluated at the initial and final stages of storage. For assessment of physiological weight loss, onion bulbs of each replication of each treatments were separately weighed using digital electronic balance (Xpart TM 40g-40 kg) at different days of observations (20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260 and 280 days after irradiation). The cumulative percentage weight loss was calculated based on initial bulb weight (Nouri and Toofnaian, 2001). For calculation of rotting severity, onion bulbs that showed symptoms of rotting (soft and moldy) were separated out from each replication of each treatment. The separated rotten bulbs were counted and weighed at different days of observations as mentioned earlier. The rotting percentage was calculated using the formula, rotting (%) = (Number of rotten bulbs)/Total number of bulbs)*100. Sprouting is an important limitation for long-term storage of onions. Onion bulbs that showed symptoms of sprouting were separated out from each replication of each treatment. The separated sprouted bulbs were counted at the different days of observations as mentioned earlier. The sprouting percentage was calculated using the formula, sprouting (%) = (Number of sprouted bulbs)/Total number of bulbs)*100. For documenting bulb size, randomly selected 10 onion bulbs from each replication were selected at the 1st day after irradiation and numbered. The bulb diameters of the selected onion bulbs were taken from two directions by a slide calipers (Mitutoyo) and average was taken. Similar measurements were also taken at the 200 days after irradiation. For recording bulb colour, randomly selected 5 onion bulbs from each replication of each treatment were selected. Colour was recorded at the 1st and 200th day after irradiation using a Standard Colour Chart (Royal Horticulture Society, UK). Bulb texture (firmness) was recorded from randomly selected 5 onion bulbs from each replication (kept for destructive sampling) of each treatment at the 200th day after irradiation using a Penetrometer (Fruit Pressure Tester, Model FT 327). Total soluble solids (TSS) were assessed from the randomly selected bulbs (kept for destructive sampling) at the 0, 30, 60, 90, 120, 150,180 and 210 days after irradiation. Bulbs were crushed by mortar and pestle and juice was extracted by passing through a cheese cloth. Then, TSS was recorded using a Refractometer (0-32% BRIX, ERMA) by taking a drop of juice on the prism and expressed as ^{o}Brix. pH of the onion bulbs subjected to irradiation treatments was recorded using a pH Meter (JENWAY, pH/mV Temperature Meter, Model 3520). Twenty (20) g onion bulb (chopped) was mixed with 100 mL distilled water and blended. Then the blended pulp was filtrated through cheese cloth and final volume was made up to 200 mL (Ranganna, 1979). The pH of the prepared solution (onion juice) was determined at 0, 30, 60, 90, 120, 150 and 180 days after irradiation.

Statistical analysis

The experiment was laid out in a completely randomized design (CRD) with 3 replications (rigid plastic crate with 5 kg bulbs replicate^{-1}). Data were analyzed using analysis of variance by Statistix 10 (version 10.0 Analytical software USA). Statistically significant differences among the different doses were identified by LSD at a 5% level of significance.

Results

Weight loss

The irradiation treatments exerted significant effects to influence weight loss of onion bulbs during storage (Figure 2). Results revealed that after 40 days of storage at ambient condition, weight loss was more or less similar in the untreated bulbs (control) and the irradiated bulbs. Weight loss increased afterwards, and was the highest in the non-radiated control bulbs at all the days of observation at ambient condition, which clearly manifested remarkable advantage of applying gamma irradiation on reducing weight loss of stored bulbs (Figure 2). Substantial loss in weight (84.80%) was recorded in untreated control bulbs at the 280th day of storage, whereas significantly reduced levels of weigh losses (49.75, 47.72, 48.49 and 51.65%) were recorded in bulbs treated with 50 100, 150 Gy and 200 Gy gamma rays, respectively (Figure 2). Statistically similar impacts were produced by the different doses of gamma irradiation examined. However, 100 Gy showed the minimal weight loss (47.72%) as compared to those of other doses during the entire period of investigation.

Levels of postharvest rots

Irradiation treatments caused significant effects in reducing storage rots of onion bulbs. Levels of rots increased with time but at varying rates. Onion bulbs irradiated with 100 and 150 Gy remarkably reduced the rates of storage rots during entire period of observation. At the end of storage (280th day), the levels of rots were 26.31, 22.96, 14.69, 19.40 and 23.40% at 0, 50, 100, 150 and 200 Gy, respectively (Figure 3), where the highest level of rots (26.31%) was recorded in the non-radiated control bulbs, which showed statistically identical results with 50 and 200 Gy indicating less effectiveness of both the very low and very high doses of radiation in reducing rot percentage. On the other hand, the lowest level of rots (14.69%) was recorded in bulbs treated with 100 Gy gamma radiation followed by 150 Gy, although the effects were statistically identical (Figure 3).

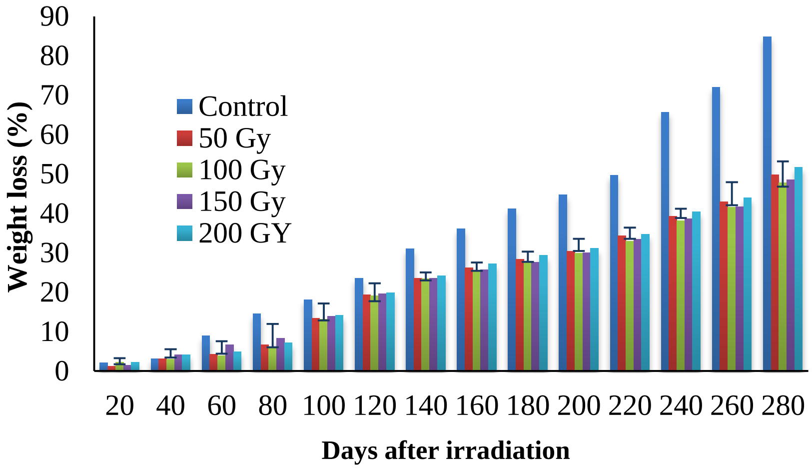

Figure 2. The weight loss (%) of the non-irradiated and irradiated onion bulbs at different days after irradiation. At each day of irradiation, the vertical bar indicates LSD at the 5% level of significance

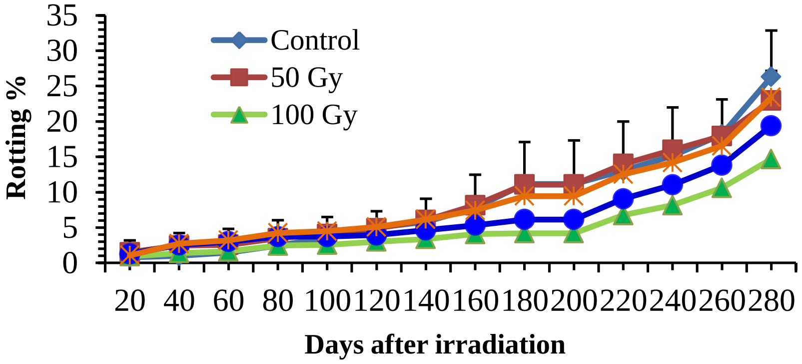

Figure 3. Levels of rots of the non-irradiated and irradiated onion bulbs at different days after irradiation. At each day of irradiation, the vertical bar indicates LSD at the 5% level of significance

Sprouting inhibition

Results of the present study revealed that at ambient condition, there was no sprouting up to the 60th day of irradiation (DAI) in both the non-irradiated control and the irradiated bulbs. The untreated control bulbs started to sprout from the 60th DAI (0.11%), which sharply increased to 89.05% at the 280th DAI at ambient condition (Table 1; Figure 4, 5). Strikingly, a complete inhibition of sprouting was achieved in the irradiated bulbs irrespective of doses (Table 1; Figure 4, 5). It was observed that radiation treatments of 50, 100, 150 and 200 Gy were equally effective in sprout inhibition of onion bulbs during long-term storage (up to 280 days) at ambient temperature.

Table 1. Levels of sprouting of non-irradiated control and irradiated onion bulbs at different days after irradiation (DAI)

Irradiation treatments (Gy)	**Levels of sprouting (%) at different DAI**						
	40	80	120	160	200	240	280
0	0.00	0.23**a**	2.1**a**	24.97**a**	59.36**a**	75.99**a**	89.05 **a**
50	0.00	0.00**b**	0.0**b**	0.00 **b**	0.00**b**	0.00**b**	0.00 **b**
100	0.00	0.00**b**	0.00**b**	0.00 **b**	0.00**b**	0.00**b**	0.00 **b**
150	0.00	0.00**b**	0.00**b**	0.00 **b**	0.00**b**	0.00**b**	0.00 **b**
200	0.00	0.00**b**	0.00**b**	0.00 **b**	0.00**b**	0.00**b**	0.00 **b**
Level of Sig.	-	*	**	**	**	**	**
CV (%)	-	0.16	0.38	1.16	3.67	1.93	3.43

* = Significant at 5% level; ** = Significant at 1% level; ns = Not significant.

In a column, the figures having common letter do not differ significantly at 5% level of significant.

Figure 4. The experimental view (A- 180 days after irradiation) and variation among treatments in terms of sprout inhibition (B- 200 days after irradiation)

Figure 5. The mostly sprouted and unmarketable bulbs in un-treated control (A- 240 days after irradiation), and un-sprouted and marketable bulbs (B- 240 days after irradiation at 100 KGy)

Physico-chemical changes

Important physico-chemical properties like bulb size, bulb texture, TSS and pH were measured at different days after irradiation. Results showed that bulb size decreased with time. The initial bulb sizes under irradiation treatments at 0, 50, 100, 150 and 200 Gy were 2.85, 3.04, 2.84, 3.12 and 2.94 cm, and which reduced to 2.39 (16.14%), 3.01 (0.98%), 2.79 (1.76%), 3.08 (1.28%) and 2.86 cm (2.72%) at the 280th day after irradiation, respectively (Table 2). Texture of bulb is an important quality parameter of onions, and was measured at the end of the observation. Maximum force (5.40 kg) was required to penetrate an 8 mm diameter probe into untreated (control) onion bulbs. In contrast, the irradiated bulbs irrespective of doses required lesser forces (3.29-4.70 kg) (Table 2). Initial colour of onion bulbs was red brown (RHS 171A) during setting up of the experiment. At the 280th day after storage, the non-irradiated control bulbs turned purple brown (RHS 166A) and the irradiated bulbs retained the same colour (red brown; RHS 171A) (Table 2).

TSS contents were not significantly affected due to different doses of gamma radiation during the period of investigation (Table 3). TSS content slightly increased with time in both control and the irradiated bulbs, and ranged from 11.00 to 16.17 ^{o}Brix at 1 and 210 days after irradiation, respectively (Table 3). pH of onion bulbs gradually increased with time irrespective of radiation doses. The maximum pH (6.16) was recorded in the non-radiated control bulbs at the 210th day after irradiation, while the irradiated bulbs showed significantly lower levels except at 200 Gy (Table 4). However, differences among the irradiation treatments were not significant up to 180 days after irradiation, and the variation was significant afterwards where the untreated control and 200 Gy had higher levels of pH (Table 4).

Table 2. Size, texture and colour of the irradiated and non-irradiated onion bulbs at 1 and 280 days after irradiation

Radiation dose (Gy)	**Bulb size (cm dia.) at different DAI**		**Texture (Kg force with 8 mm probe) at 280 DAI**	**Bulb colour (Standard Colour Chart) at different DAI**	
	1	**280**	**280**	**1**	**280**
0	2.85	2.40d	5.40a	Red brown (RHS 171A)	Purple brown (RHS 166A)
50	3.04	3.01ab	3.91c	Red brown (RHS 171A)	Red brown (RHS 171A)
100	2.84	2.80c	4.70b	Red brown (RHS 171A)	Red brown (RHS 172A)
150	3.12	3.08a	4.62b	Red brown (RHS 171A)	Red brown (RHS 171A)
200	2.94	2.87bc	3.29d	Red brown (RHS 171A)	Red brown (RHS 172A)
Level of sig.	ns	**	**	-	-
CV	4.76	3.98	1.46		

** = Significant at 1% level; ns = Not significant; DAI = days after irradiation.

In a column, the figure (value) having common letter do not differ significantly at 5% level of significant.

Table 3. TSS (^{o}Brix) of onion bulbs of the irradiated and non-irradiated bulbs at different days after irradiation (DAI)

Radiation doses (Gy)	**TSS (^{o}Brix) of the irradiated and non-irradiated onion bulbs at different DAI**							
	1	**30**	**60**	**90**	**120**	**150**	**180**	**210**
0	12.33	13.00	13.67	13.83	14.50	14.67	14.83	16.17a
50	11.00	12.83	13.50	13.00	13.83	14.50	14.67	15.17b
100	12.67	12.93	13.67	14.33	14.43	14.54	15.44	15.67ab
150	12.00	12.83	13.83	14.83	14.67	14.67	14.83	15.00 b
200	12.00	13.00	13.33	13.17	13.83	14.50	14.67	16.00a
Level of Sig.	ns	ns	ns	ns	ns	ns	ns	*
CV (%)	8.90	11.1	6.61	11.64	13.58	7.84	7.34	2.68

* = Significant at 5% level; ** = Significant at 1% level; ns = Not significant.

In a column, the figure (value) having common letter do not differ significantly at 5% level of significant.

Table 4. pH of onion bulbs of the irradiated and non-irradiated bulbs with time after irradiation

Radiation doses (Gy)	**pH of the irradiated and non-irradiated onion bulbs at different DAI**							
	1	**30**	**60**	**90**	**120**	**150**	**180**	**210**
0	5.49	5.69	5.83	5.83	5.88	5.84	6.11a	6.16a
50	5.66	5.69	5.69	5.95	5.96	5.85	6.09a	6.11b
100	5.71	5.74	5.85	5.85	5.87	5.87	5.99b	6.02c
150	5.75	5.763	5.58	5.56	5.72	5.78	6.08a	6.11b
200	5.81	5.82	5.82	5.85	5.85	5.87	6.11a	6.15ab
Level of Sig.	ns	ns	ns	ns	ns	ns	*	**
CV (%)	5.59	6.90	4.76	3.40	2.08	2.09	0.66	0.41

* = Significant at 5% level; ** = Significant at 1% level; ns = Not significant.

In a column, the figure (value) having common letter do not differ significantly at 5% level of significant.

Discussion

Different levels of gamma irradiation were evaluated for long-term storage of a commercially-important onion variety of Bangladesh called Taherpuri. Physiological loss in weight, postharvest rots, sprout inhibition, and various physico-chemical properties of onions subjected to radiation treatments were investigated. Weight loss is an important limitation for conventional storage of onions at ambient condition and subsequent marketing and distribution. The main causes of weight loss of stored onions include moisture loss, sprouting, shrinkage, drying and respiration. In the present investigation, irradiation significantly reduced physiological weight loss during storage, and 100 Gy showed the minimal weight loss (47.72%) as compared to those of other doses (0 Gy, 50 Gy, 150 Gy and 200 Gy) during the entire period of investigation, and which results may be due to reduced moisture loss, sprout inhibition and rots. The present findings are in accordance with the Sharma *et al.* (2020), who reported that gamma irradiation with 120 Gy showed minimum weight loss (%). Abdullah *et al.* (2018) reported that irradiation dose of 150 Gy showed lesser weight loss of onions. The present results suggests that 100 Gy gamma-irradiated onions bulbs (cv. Taherpuri) can be stored up to 280 days (≈ 9 months) at ambient condition with significantly reduced loss in weight (47.72 %).

One of the major reasons for postharvest loss of onions is due to storage rots caused mainly by pathogenic microorganism. Globally, around 15 species of fungi and 5 species of bacteria were found responsible for diseases of onions during storage and transit (Mahmud and Manjil, 2015). Higher levels of storage rots were recorded in the non-radiated control bulbs, which showed statistically identical results with 50 and 200 Gy indicating less effectiveness of both the very low and very high doses. On the other hand, lower levels of rots were recorded in bulbs treated with modest doses of 100 and 150 Gy. This is also important to note that at the 180th day, onion bulbs irradiated with 100 Gy had only 4.01% rots, while the non-radiated control bulbs had almost three-time higher rots (11.0%). However, similar results were not found available. The reduced levels of rots due to treatment of gamma irradiation may be attributed to the inhibited fungal sporulation and subsequent growth, and reduced rates of physical and physiological changes. Hallman (2011) also reported that ionizing radiation is a viable alternative and an effective nonchemical treatment for control of postharvest disease.

Sprouting is a major problem of onion during long-term storage, especially in the winter season in Bangladesh, when dormancy breaks due to prevailing ideal sprouting temperature (18-25 °C) with consequently increased level of endogenous ethylene. The sprouted bulbs are simply unmarketable, and incur a total loss. Irradiation irrespective of doses completely inhibited sprouting of onion bulbs examined up to 280 days. These results might be due to higher ascorbic acid and other hormonal compounds like ethylene in the irradiated bulbs (Nouri and Toofanian 2001). Several researchers reported similar findings on sprout inhibition through irradiation. Tripathi *et al*. (2011) reported 33.4% sprouting after 75 days of storage in control and no sprouting in the irradiated onions bulbs. Sharma *et al*. (2020) observed no sprouting in onion bulbs treated with gamma radiation at 120 and 200 Gy during long-term (144 days) storage at ambient condition. However, the duration of sprout inhibition (280 days) as found in the present investigation, was almost double of the previous study (144 days, which may be because of difference in variety or stage of maturity. Rezaee *et al*. (2013) reported that application of irradiation to onion bulbs immediately after harvest resulted in sprout inhibition. Onion bulbs immediately after harvesting remain in active metabolic state and are more sensitive to irradiation which disrupts nucleic acids, nucleotide and hormone synthesizing system, and caused inhibition of sprouting.

Important physical parameters including bulb size, texture and colour were measured at different days after irradiation. Results showed that bulb size decreased at higher rate in untreated control bulbs as compared to irradiated bulbs. The decrease in bulb size in control bulbs (16%) at the end of storage was possibly attributed to the increased respiration and water loss. Similar reports to support the present results were not found available. Texture of bulb is an important quality parameter of onions. The non-radiated bulbs had firmer texture possibly due to higher rate of water loss and the resultant dryness of the bulbs. In contrast, the irradiated bulbs irrespective of doses required lower force to penetrate indicating lesser firmness, which may be due to minimal water loss and the retained freshness of the bulbs. Bulb colour of the irradiated bulbs remained red brown (RHS 171A) up to the end of storage duration (280 days) suggesting retention of external quality of the irradiated bulbs. In contrast, the colour of the non-radiated bulbs turned purple brown (RHS 171A) indicating deterioration of quality. Similar reports to support the present findings were not found available.

Chemical parameters including TSS and pH of the treated and un-treated onion bulbs were examined. TSS contents were not significantly affected due to different doses of gamma radiation during the period of investigation. TSS content slightly increased with time possibly due to decomposition of starch into sugars resulted in increased TSS in both control and the irradiated bulbs. Petropouls *et al.* (2016) also worked with four onion varieties and found non- specific trend of decreasing or increasing TSS during storage. Most importantly, levels of pH of onion bulbs gradually increased with time irrespective of radiation treatments. The increase in pH may be due to gradual reduction of acidity during storage. However, treatment effects were not significant up to 180 days after irradiation, and the variation was significant afterwards. The untreated control bulbs had significantly higher pH values as compared to the irradiated bulbs except at 200 Gy.

Gamma radiation significantly prolonged storage life of onion bulbs along with complete inhibition of sprouting and reduction of disease severity and weight loss. It was observed that gamma radiation at 100 Gy resulted in the minimal weight loss (47.72%), rotting (14.69%) and sprouting (0%) up to 280 days of storage at ambient condition. In contrast, weight loss (84.80%), rotting (26.31%) and sprouting (89.05%) were the highest in the untreated control bulbs at the same day of observation. Irradiation dose of 100 Gy was found to maintain suitable TSS, pH, taste and did not cause unacceptable changes in colour and size. In conclusion, application of gamma radiation at 100 Gy was found to be very effective in extending shelf life of onions (cv. Taherpuri), and a maximum storage duration of 280 days was recorded in the present investigation. Further studies are suggested to conduct combining with promising postharvest treatments like modified atmosphere (MA) packaging along with detailed investigation of quality and safety parameters for further refinement of the technology.

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