Food Research 6 (4) : 47 - 58 (August 2022)
Journal homepage: https://www.myfoodresearch.com

FOOD RESEARCH

REVIEW

Potential of gamma irradiation on postharvest quality of tomato (*Solanum lycopersicum* L.): a review

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Article history:
Received: 28 June 2021
Received in revised form: 29 July 2021
Accepted: 19 January 2022
Available Online: 3 July 2022

Keywords:
Gamma irradiation,
Tomato,
Postharvest,
Shelf life,
Quality

DOI:
https://doi.org/10.26656/fr.2017.6(4).464

Abstract

Tomato is the most consumed fruit, and an important agricultural product. Losses associated with tomatoes are mainly due to their perishability. Food irradiation using gamma rays is one of the preservation methods which can be used to extend the storage duration while maintaining the sensory quality of tomatoes. This review discussed the potential of gamma irradiation on the postharvest quality aspects of tomatoes through radiation sterilisation. Gamma irradiation has also been proven suitable in delaying the rapid maturity of tomatoes, thus extending their storage life. Doses between 0.5 and 2.5 kGy have been found to maintain the colour, texture, taste, flavour, and overall sensory quality of tomatoes. Gamma irradiation has also been well adopted to control foodborne spoilage and pathogenic microorganisms. Nowadays, many countries allow food irradiation technology as a suitable and cost-effective solution for the problems caused by various types of insects and microorganisms in fresh produce and food products thereof. This review will thus provide updated and in-depth information useful for the producers, manufacturers, and policymakers alike in the adoption of gamma irradiation for tomato preservation.

1. Introduction

Tomato (*Solanum lycopersicum* L.) is the most widely spread and cultivated Solanaceae vegetable crop. In tropical and subtropical parts of the world, it is available throughout the year. The major producer of tomatoes is China (34.77%; 63 mil tonnes), followed by India (19 mil tonnes), then Turkey (13 mil tonnes) as shown in Figure 1 (FAOSTAT, 2019). Tomato is climacteric in nature, and its cultivation serves as a source of income for developing regions of the world (Arah *et al*., 2015).

As with many other crop commodities, tomato is also subject to postharvest losses. These pose significant difficulties to farmers, processors, and retailers, as well as hindering the producer country's exportation (Arah *et al*., 2015). With the advancement of crop research, management, and technology, nowadays, it is shown that the trends are shifting from quantity aspects to quality aspects of agricultural produce (Oko-Ibom and Asiegbu, 2007). Fungi and bacteria are commonly associated with postharvest diseases and decay of tomatoes, with the grey mould diseases and soft rot, which are the important postharvest diseases of tomatoes worldwide. According to Petrasch *et al*. (2019), *Botrytis cinerea*, *Fusarium acuminatum*, and *Rhizopus stolonifer* are the most common fungal pathogens of tomatoes, which actively attack during the ripening stage. Various methods have already been introduced to extend the shelf life of tomatoes including the application of 1-MCP, $CaCl_2$, and active packaging to reduce the microbial contamination of tomatoes. In recent years, much research has been conducted to investigate the effects of different ionising

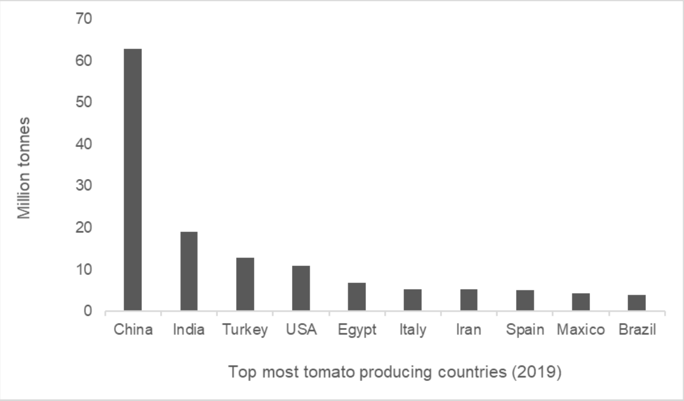

Figure 1. Leading tomato producing countries. Source: FAOSTAT (https://www.fao.org/faostat/en/#data/QCL)

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radiations such as X-rays, UV-rays, and gamma rays on fresh fruits and vegetables to maintain their quality and prolong their shelf life. Of these, gamma irradiation is considered one of the most suitable methods for the preservation and shelf-life enhancement of tomatoes for international trade.

The present review, thus, discussed the effect of gamma irradiation on the overall sensory quality, marketability, and shelf life of tomatoes, as well as identified the research gaps for future consideration.

2. Ionising radiation

Ionising radiation is a type of energy that can move as particles (electron beams) or as waves (X-rays and gamma rays) (IAEA, 2015). Radiation is ionising if it has sufficient energy to remove the electrons from atoms or molecules, thus ionising them, hence the name (Dertinger and Jung, 2013). The electron beam technology enables the acceleration of electrons to near the speed of light using a linear accelerator and magnetic fields, 5-10 MeV (mega electron volts) (IAEA, 2015). Since the electrons cannot penetrate extremely far into foodstuff (only approximately 6-8 cm depth, relatively thin or low-density products), they can be used to irradiate the packaging of food products, or the food exterior surface (Fan and Niemira, 2020). X-rays, on the other hand, are high-energy photons, produced as a result of high-energy electrons (up to 5 MeV) that strike a metal plate (tungsten or tantalum alloys), and are generally used for medical purposes (Fan and Niemira, 2020). X-rays have high penetrative power as compared to electron beams but have a poor energy conversion rate (Johnson *et al*., 2004; Suresh *et al*., 2005; IAEA, 2015).

2.1 Gamma irradiation

Gamma irradiation has been performed as a postharvest technique for the preservation of fruits and vegetables for many years (Antonio *et al*., 2012). Low doses application of gamma irradiation could extend the storage duration by decreasing the biological activity of fruits and vegetables without imparting any harmful alteration of internal composition (Ahuja *et al*., 2014). The application of gamma irradiation for the management of fruits and vegetables acts as an effective alternative to fumigation or other harmful chemicals. Postharvest techniques using gamma rays are of growing interest that can be done at ambient temperature and humidity and have shown immense effectiveness in the destruction of harmful foodborne microorganisms without any effects on the nutritional and sensory attributes of the produce (Bidawid *et al*., 2000). The application of gamma irradiation is thus a feasible method for reducing postharvest degradation, extending the storage life of crop commodities, and retaining the desirable quality of fresh fruits and vegetables (Fan, 2012). Many investigations have also revealed that gamma rays can increase the storage duration of different tropical and subtropical fruits due to the inactivation or elimination of harmful microorganisms (Olanya *et al*., 2015). Gamma rays are within the electromagnetic spectrum and consist of short wavelengths with high energy and high penetrative power (30-40 cm). Gamma irradiation produced from the spontaneous breakdown of radionuclides of certain isotopes like Cobalt-60 with a half-life of 5.27 years, and Cesium-137 with a half-life of 30 years are commonly used in food irradiation (Fan and Niemira, 2020).

Gamma-ray source continuously/spontaneously emits radiation, even when not in use (IAEA, 2015). Gamma irradiation photons stimulate atoms and can release high-energy electrons which cause the breakdown of water molecules into radicals, which in turn cause structural damages/changes to DNA structure (Fan and Niemira, 2020). With high penetrative power, there must be protection for the workers against harmful exposure by predesigned precautionary measures. Depending on radiation sources and required doses, the shielding design can either consist of 2 m concrete or 1 m steel, iron, or lead. It has been established that gamma irradiation avoids postharvest degradation and extends shelf life by slowing the ripening/maturation/senescence of crop commodities (Mostafavi *et al*., 2010).

3. Factors influencing gamma irradiation efficiency on fresh produce

Among the numerous considerations that have already been estimated as affecting the efficiency of the ionising radiation (Hallman *et al*., 2010), the amount of oxygen is the most important factor that has previously impacted the management process of the treatments. If the gamma irradiation takes place under hypoxic conditions (low oxygen conditions), its efficiency could decrease. Therefore, it is prohibited to irradiate the produce under hypoxic conditions (USDA, 2016). The penetration capability and the dose rate are the two main physical properties that differentiate gamma irradiation from electron beams, electron beams have low penetration capability but high dose rate, whereas gamma rays have high penetration capability but low dose rate (IAEA, 2015). Dose rate can directly affect the efficacy, a faster dose rate quickly overcomes the radiation damage repair mechanisms (Hallman and Blackburn, 2016). The high dose rates result in depletion of oxygen molecules which increases the efficacy and the nature of destruction exerted by the irradiation. Fresh commodities and pests (pathogens and insects) have different levels of tolerance to dose rate and sources of irradiation. Other factors influencing the efficiency of irradiation are discussed in the following sub-chapters.

3.1 Dose rate

According to Codex Alimentarius (Ferreira *et al.*, 2017), the ultimately absorbed doses on food materials should not exceed 10 kGy. The absorbed dose is the measurement of the ionising energy absorbed by a unit mass of an individual substance and is expressed in Gray (Gy; named after British physicist Louis Harold Gray), where 1 Gy is correspondent to the assimilation of 1 Joule per kg. The precise quantity of absorbed dose in a batch is critical for determining and monitoring the effectiveness and assurance of consumers' food safety (IAEA, 2015). A dosimeter is used to calculate the required doses for irradiation of a product, and also calculate the absorbed doses. The use of gamma irradiation on foodstuff including fresh commodities have been well established and extensively researched since the 1950s, showing no harmful hazards to human health (Sommers *et al.*, 2006). The applications of gamma irradiation on different food materials and their indicative dose ranges are shown in Table 1.

3.2 Environmental conditions during irradiation (temperature and humidity)

The environmental conditions such as temperature and humidity during irradiation largely affect the irradiation process (Hallman *et al.*, 2010). Temperature and humidity could promote the rapid decay of perishable fruits and vegetables. Therefore, environmental conditions pre- and post-irradiation should be maintained to retain the quality of the products. Generally, the storage period pre-irradiation should be as short as possible. To apply irradiation on dried fruits for controlling insect pests, the moisture content should not be more than10–12% for nuts, and 20–35% for other fruits (IAEA, 2015). Similarly, for fresh and frozen fruits and vegetables, the cold chain should be maintained before and after irradiation; the temperature should be within 4°C for fresh meats and poultry, and 3°C for fresh fish and seafood. The required temperature for frozen products is under −18°C and the irradiation should be performed at a temperature similar to that during product processing (IAEA, 2015).

4. Benefits of gamma irradiation of tomato

The application of gamma irradiation on tomatoes at low doses (0.75-1.0 kGy) has been investigated and found appropriate for its shelf-life extension (FDA, 1995). The extension of postharvest shelf life and different quality attributes of tomatoes using gamma irradiation is summarised in Table 2.

4.1 Shelf-life extension

The most important concern in tomato production is its extremely short postharvest shelf life which poses a threat to the farmers which in turn forces them to discharge the commodity at very low prices (Kumar *et al.*, 2014). As earlier mentioned, the losses of a large number of crops by insect infestation and microbial colonisation can be controlled and minimised by irradiation (Ventura *et al.*, 2010). Tomato cultivars 'Amani' and 'Beto 86' were subjected to gamma irradiation at 0.25, 0.5, and 1.0 kGy, and it was found that the treatment drastically decreased the rate of respiration in both cultivars, and significantly suppressed the activity of ethylene-forming enzymes, which ultimately extended the shelf life (Adam *et al.*, 2014). In another work, the tomato cultivar 'Pusa Rubi' was collected from the regional market and gamma-irradiated at dose ranges of 0.75 to 1.0 kGy. It was found that the spoilage microorganisms were significantly reduced, and the tomato postharvest shelf life was extended (Singh *et al.*, 2016). Kumar *et al.* (2014) demonstrated that the tomato cultivar 'Pusa Rubi' harvested at the green maturity stage and irradiated at different doses resulted in the delay of the ripening process, thus extending its storage duration.

4.2 Microbial disinfection

Ionising radiation can effectively control insects and microorganisms on food products by disrupting/

Table 1. Application of gamma irradiation on different food materials, and their indicative dose ranges (IAEA, 2015)

Dose (kGy)	Effect	Food material
< 1.0	Inhibit sprouting	Potato, garlic, onion, yam
	Delay fruit ripening	Papaya, banana, tomato
	Inactivate insects	Fresh produce
	Kill insects	Dry fish, legumes, fruits
	Inactivate parasites, protozoa, and helminths	Processed meats, fresh fruits and vegetables
1.0 to 10	Inactivate spoilage microorganisms	Strawberries, mushrooms, dried fish
	Extend shelf life	Processed and refrigerated meats, fish, ready-to-eat foods
	Inactivate non-sporulating microorganisms	Frozen meats, fish, seafood, pre-cut fruits and vegetables
> 10	Kill microorganisms	Hospital diets (for immune compromised patients), emergency ration

Table 2. Effects of gamma irradiation on postharvest shelf life and different quality parameters of tomato

Parameter	Cultivar	Radiation Dose (kGy)	Key Finding	Reference
Shelf life	Cultivated variety	0.75 to 1.0	Extended shelf life	FDA (1995)
	Amani and Beto 86	0.25, 0.5 and 1.0	Extended shelf life	Adam *et al.* (2014)
	Pusa Rubi	0.75 to 1.0	Extended shelf life	Singh *et al.* (2016)
Ethylene	Amani and Beto 86	0.25, 0.5 and 1.0	Suppressed the activity of	Adam *et al.* (2014)
	Cherry tomato	1	Suppressed the activity of the	Larrigaudiere *et al.* (1990)
Microorganisms	Pusa Rubi	0.75 to 1.0	Reduced the spoilage	Singh *et al.* (2016)
	Peeled and ready-to-	1	4-log decrease of *Listeria monocytogenes*	Lafortune *et al.* (2005)
	Bell peppers	1	4-log decrease of *Listeria monocytogenes*	Farkas *et al.* (1997)
	Sliced tomato	0.5	Reduced microbial counts	Prakash *et al.* (2002)
	Pre-cut tomato	0.5	Improved microbiological quality	Mohacsi-Farkas *et al.* (2014)
Ripening	Pusa Rubi	0.75 to 1.0	Delayed ripening	Singh *et al.* (2016)
Sensory quality	Pre-cut tomato	0.5	Maintained sensory and	Mohacsi-Farkas *et al.* (2014)
	Pusa Rubi	0.5 to 3.0	No significant changes	Singh *et al.* (2016)
	Pusa Rubi	4	Significantly decreased the scores	Singh *et al.* (2016)
Respiration	Amani and Beto 86	0.25, 0.50 and 1.0	Reduced respiration rate	Adam *et al.* (2014)
	Cherry tomato	1	Reduced respiration rate	Larrigaudiere *et al.* (1990)
Weight loss	Cultivated variety	0.5	Reduced weight loss	Lester (1996)
	Cultivated variety	2.0 to 3.0	Reduced weight loss	Mitsuhashi *et al.* (1998)
	Pusa Rubi	1.5	Reduced weight loss	Singh *et al.* (2016)
	Amani and Beto 86	0.25, 0.50 and 1.0	Reduced weight loss	Adam *et al.* (2014)
β-carotene	Local variety	0.5 and 1.0	Showed significantly lowest amount of β-carotene	Kumar *et al.* (2014)
Lycopene		1	Showed significantly lowest	Mditshwa *et al.* (2017)
Colour change	Pusa Rubi	0.75 to 1.0	No significant differences	Singh *et al.* (2016)
	Pusa Rubi	2	Lower anthocyanin content	Singh *et al.* (2016)
Firmness	Amani and Beto 86	0.25 to 1.0	Became soft after 24 days	Adam *et al.* (2014)
Ascorbic acid	Amani and Beto 86	0.25 to 1.0	Maximum level of ascorbic acid was observed	Adam *et al.* (2014)
TSS	Armany	0.25 to 1.0	5.67% TSS were reached in 21	Adam *et al.* (2014)
	Cultivated variety	3.2 to 5.7	Increased TSS values	Guerreiro *et al.* (2016)
	Pusa Rubi	0.75 to 2.0	Titratable acidity was	Singh *et al.* (2016)
Antioxidant	Fresh tomato	Low doses	A high amount of antioxidant	Fan *et al.* (2005)
	Money Maker and	Low doses	A higher amount of flavonoid and flavonol were observed	Castagna *et al.* (2014)
	Cherry tomatoes	3.2 and 5.7	The lowest total phenolic contents were observed	Guerreiro *et al.* (2016)
	Cultivated variety		Reduced the concentration of phenolic contents	Schindler *et al.* (2005)
	Local variety	0.5 and 1.0	Antioxidant enzyme activity (CAT), (APX), and (SOD)	Kumar *et al.* (2014)
	Cherry tomato	1.3	Maximum values in FRAP assay	Mendes *et al.* (2020)
	Cherry tomato	5.7	Reduced activity in FRAP assay	Guerreiro *et al.* (2016)
	Local variety	1	Increased activity in CUPRAC	Kumar *et al.* (2014)

destroying their cellular functions (Acheson *et al*., 2001; Fan *et al*., 2009). At the molecular level, irradiation can break down the DNA bonds, thus leading to inversion, addition, or deletion of nucleotides on the DNA strands. This eventually disrupts normal cellular functions (Follett, 2014). The tolerance towards irradiation is different for various life stages of insects; thus, the effective dose rate should be known and applied accordingly to achieve the desired purpose (Hallman and Blackburn, 2016).

Typically, gamma irradiation doses ranging from 0.2 to 0.8 kGy are efficient to reach a 1-log decline for bacteria, whereas viruses and fungi have more survival capacity, thus requiring a higher dose range of 1.0 to 3.0

kGy to achieve a similar reduction (Niemira and Sommers, 2006). Common foodborne diseases which often lead to hospitalisations and deaths are usually caused by bacteria (Mead *et al.*, 1999). It has been shown that irradiation is effective for inactivating common foodborne bacteria such as *Escherichia coli* O157:H7 and *Salmonella* spp. on fruits and vegetables. Irradiation reduces the surface microbial load significantly by inactivating and altering their physiological functions, rupturing their cell membrane, and also by exerting cell wall damage (Lado and Yousef, 2002). Through irradiation, microorganisms are also prevented from reproducing due to the DNA damage which is brought about by the direct attack of the ionising irradiation, or the indirect attack of oxidative radicals derived from the radiolysis of water in the cell (Lado and Yousef, 2002).

The irradiation sensitivities among the microorganisms are related to their physical and chemical structures, and also to their ability to recover from irradiation damage (Farkas, 2006). Singh *et al.* (2016) proved that the effects of gamma irradiation on the microbial community of tomatoes at low doses of 0.75 kGy significantly decreased the total plate count (TPC) and yeast and mould count (YMC). A similar irradiation dose also resulted in the complete removal of coliform bacteria. Prakash *et al.* (2002) demonstrated that 0.5 kGy irradiation could reduce microbial counts of sliced tomato, and improve its storage life without any undesirable effects or organoleptic changes. Mohacsi-Farkas *et al.* (2014) demonstrated that gamma irradiation on pre-cut tomatoes led to microbial disinfection, shelf-life extension, and sensory and nutritional quality retention. The regeneration of yeasts and moulds during the storage of tomatoes following irradiation is a common phenomenon. Therefore, the required dose should be higher than that for bacteria to ensure successful inactivation (Singh *et al.*, 2016).

4.3 Postharvest quality

4.3.1 Respiration

The increase in respiration rate of climacteric fruits such as tomatoes during the maturity stage produces free radicals which could lead to oxidative stress. Irradiation could reduce this by reducing the respiration rate of the fruits (Kumar, 2014). Adam *et al.* (2014) demonstrated that harvested mature green tomato cultivars ‘Amani’ and ‘Beto 86’ treated with 0.25, 0.50, and 1.0 kGy of gamma rays resulted in the extension of storage duration up to 24 days as compared to the control tomato which reached the final climacteric peak after only nine days. Larrigaudiere *et al.* (1990) demonstrated that cherry tomato treated with 1.0 kGy irradiation decreased the respiration rate due to the stimulation of mRNA enzymes. A decrease in weight loss was observed in tomatoes following irradiation at low doses as the respiration rate was reduced, and the climacteric peak, ripening, and senescence were delayed (Lester, 1996). Conversely, an increase in weight loss was observed in tomatoes following irradiation at higher doses (2.0-3.0 kGy) which might be the result of severe cell membrane degeneration (Mitsuhashi, 1998).

4.3.2 Ethylene production

Tomato is climacteric in nature, and an increase in ethylene production can quicken maturity and senescence. Ethylene production can be efficiently decreased by applying 1 kGy gamma irradiation which inhibits the ethylene-forming enzymes namely 1-aminocyclopropane-1-carboxylate synthase (ACC synthase) and 1-aminocyclopropane-1-carboxylate oxygenase (ACC oxidase) (Kumar *et al.*, 2014). This is also corroborated by Larrigaudiere *et al.* (1990) in cherry tomatoes. The efficiency of gamma irradiation against ethylene production is largely dependent and fluctuates with dose rates and irradiation durations. A decrease in ethylene production was detected at 1 kGy dose by Maxie et al. (1966) who demonstrated that ethylene production decreased at a higher dose rate and that the ripening process took a long time in the irradiated fruits. Further, it was found that low doses of gamma irradiation (< 1 kGy) could not decrease the ACC enzymes; hence, no effects on ethylene production (Larrigaudiere *et al.*, 1990).

4.3.3 Phytochemical composition (carotene and lycopene)

Tomato contains a wide range of phytochemicals including carotenoids (e.g., lycopene, phytoene, phytofluene, provitamin-A, β-carotene), flavonoids, and polyphenols (USDA, 2004). Tomato is a good source of flavonols; up to 98% of total flavonols are in the tomato skin in conjugated forms of quercetin and kaempferol (Stewart *et al.*, 2000). These micronutrients and phytochemicals have shown antioxidant properties of which lycopene is the most potent (Birt *et al.*, 2001). Lycopene is the pigment mainly responsible for the typical reddish colour of matured tomatoes (80-90 % of the total pigments are in ripe tomatoes) following chlorophyll degradation (Brandt *et al.*, 2006). The ripest tomato contains lycopene at about 3-5 mg/100 g (Hart *et al.*, 1995). Kumar *et al.* (2014) demonstrated that the non-irradiated sample had maximum content of β-carotene (30.99 mg/100 g FW), and 0.5 and 1.0 kGy irradiation doses showed a significant reduction to 13.58 and 15.76 mg/100 g FW, respectively. Similarly, lycopene content increased after 15 days for control, but at 1.0 kGy irradiation dose, it was reduced to 1.63 mg/100 g FW) after 15 DAI (the day after irradiation). This suggested that gamma irradiation delayed lycopene synthesis and retained the green or unripe colour of tomato for a longer duration. The observed lowest amount of lycopene content in gamma-irradiated mature tomatoes may be due to the alteration of lycopene synthesis to β-carotene by the activity of lycopene-β-cyclase (Mditshwa *et al.*, 2017).

4.3.4 Weight loss

Physiological weight loss in tomatoes is a common phenomenon that is measured by the water loss percentage after harvest and can be determined periodically throughout the storage period. Singh *et al.* (2016) demonstrated that by applying gamma irradiation at doses up to 1.5 kGy, the weight loss in tomatoes was reduced by 9.95% and 16.29% as compared to 11.7% and 18.42% in the non-irradiated samples after 14 and 21 days, respectively at ambient condition. Adam *et al.* (2014) reported that irradiated tomatoes of two cultivars showed considerably reduced weight loss as compared to non-irradiated tomatoes. The non-irradiated tomato completely rotted after 12 days of storage, while the irradiated tomato was in good condition for up to 24 days. Nevertheless, an increase in weight loss in tomatoes irradiated at higher doses of 2-3 kGy as compared to non-irradiated tomatoes has also been observed (Singh *et al.*, 2016). This indicated that the doses of irradiation could influence the weight loss of tomatoes.

4.3.5 Colour changes

Colour is a significant indicator of tomato which is influenced by pigments such as anthocyanin. Colour is essential in determining the maturity index which is mainly used for harvesting. Singh *et al.* (2016) demonstrated that the anthocyanin content of tomatoes was unchanged following irradiation at low doses. At higher doses (> 2.0 kGy), however, lower anthocyanin content was observed. This could be the result of the delay in the ripening process. The potential of gamma irradiation to delay colour development in fruits has been extensively studied worldwide; most works showed that it could significantly delay colour development by drastically reducing the respiration rate and ethylene production (Mditshwa *et al.*, 2017).

4.3.6 Firmness

The textural properties of tomatoes are determined by their cellular and histological properties such as cell wall elasticity, turgor pressure, and pectin which manifest into a combination of firmness, crispiness, and juiciness (Bustos-Griffin *et al.*, 2012). Adam *et al.* (2014) demonstrated that unirradiated tomatoes became less firm after 12 days of storage, while irradiated tomatoes at doses 0.25-1.0 kGy became similar after 24 days. Similar findings were also observed by Bu *et al.* (2013) who evaluated the firmness of cherry tomatoes following UV-C radiation and reported that the desirable firmness retention was found in irradiated tomatoes after 35 days at 18°C storage condition. However, contradictory results have also been documented. Fan *et al.* (2008) reported that fresh fruits and vegetables irradiated at higher doses of gamma irradiation constituted a loss of firmness.

4.3.7 Ascorbic acid

Ascorbic acid in tomatoes is hypersensitive to the effects of gamma irradiation, and a low dose of 0.5 kGy could maintain its high level for up to 20 days as compared to control (Adam *et al.*, 2014). The loss in ascorbic acid content beyond the climacteric stage during storage could be attributed to the increase in oxidative activity (Snauwaert, 1973). This can be prevented by irradiation which can convert ascorbic acid into dehydro-ascorbic acid, which in turn can be re-converted to ascorbic acid (Adam *et al.*, 2014). Similar findings were reported by Loro *et al.* (2018) who irradiated tomatoes at 1.0 kGy and 1.5 kGy, both of which retained 6.39 mg/100 g ascorbic acid as compared to the unirradiated sample (6.30 mg/100 g). Low irradiation doses of 1.0 kGy have been found to exert no significant changes on the organoleptic and sensory parameters of tomatoes (Mohácsi-Farkas *et al.*, 2014).

4.3.8 Total soluble solids

The total soluble solids (TSS) in tomatoes, which are measured in degree Brix (°Bx), are a factor of commercial importance since the TSS influences taste and flavour. The TSS are different types of sugar, mainly glucose and fructose (Beckles, 2012). As the tomato ripens, the TSS increase (Ahmed and Tariq, 2014). The TSS is principally influenced by the whole amount of sugar contents in tomatoes (Adam *et al.*, 2014). Guerreiro *et al.* (2016) demonstrated that gamma irradiation had no effects on the TSS of cherry tomato at 3 kGy and 5 kGy, but increased at 3.2 kGy to 5.7 kGy. This might be related to the radiolysis of sugar, thus leading to the increase in the TSS. Nevertheless, the TSS has also been shown to decrease in tomatoes irradiated with different doses, with the unirradiated tomato maintaining the TSS during the evaluation period (Loro *et al.*, 2018).

4.3.9 Titratable acidity

The titratable acidity (TA) is the most significant parameter which influences the flavour of fruits. The TSS/TA ratio determines the consumer's organoleptic sensitivity to sweet and sour as compared to only TSS or TA individually (Hamadziripi *et al.*, 2014). During tomato ripening, TA was observed to increase and gradually decrease after the breaker stage. The TA was also observed to decrease in gamma-irradiated (0.75 to 2.0 kGy) tomatoes as compared to the control (Singh *et al.*, 2016). The retention of TA is the indicator of delayed ripening. Although very little attention is focused on the potential effects of irradiation on the TA or TSS/TA ratio of tomatoes nowadays, it is nevertheless necessary since this determines the organoleptic and sensory attributes.

4.3.10 Sensory attributes

Sensory attributes of tomato include colour, texture, flavour, and overall acceptability. Singh *et al.* (2016) performed gamma irradiation on tomatoes at 0.5 to 4.0 kGy doses and found that 0.5 to 3.0 kGy exerted no significant changes on tomato colour as compared to control. However, the 4.0 kGy dose significantly decreased the sensory scores as compared to the control. They concluded that the application of gamma irradiation at low doses of 0.5 kGy was significantly desirable to that of untreated tomato in terms of colour, texture, flavour, and overall acceptability. Salunkhe *et al.* (1974) also observed that most pigments present in tomatoes were sensitive to irradiation and that the levels of sensitivity significantly differed with different doses. The sensory attributes of the irradiated tomato at 0.5 to 1.5 kGy doses were equally acceptable as measured by the Hedonic Scale method.

4.3.11 Antioxidant properties

The total phenolic contents including flavonoids and the total antioxidants are essential microelements in tomatoes due to their involvement in nutritional and sensory quality (Shabaz *et al.*, 2014). The total phenolic contents are normally high 15 days after harvest followed by a significant decline at the final stage of maturity. Fan *et al.* (2005) found that irradiated tomatoes had a high amount of antioxidants as compared to non-irradiated tomatoes. A higher amount of flavonoids and flavonols has also been reported in irradiated tomato cultivars of ‘Money Maker’ and ‘High Pigment-10’ (Castagna *et al.*, 2014). In another case, Tomás-Barberán and Epsin (2001) reported that irradiated tomato resulted in higher phenolic contents, which were associated with several biosynthetic pathways of enzymes such as phenylalanine ammonia-lyase (PAL), a catalyst for the synthesis of phenolic compounds such as phenylpropanoids, coumarin, and flavonoids. Regarding the irradiation doses, it was observed that the highest and lowest total phenolic contents were observed following irradiation at 3.2 and 5.7 kGy, respectively (Guerreiro *et al.*, 2016). However, according to Schindler *et al.* (2005), gamma irradiation reduced the concentration of phenolic substances in conventional tomato varieties. Other authors also observed a significant decline in the total phenolic contents of fruit juice just immediately after irradiation at high doses of 5.0 kGy (Shahbaz *et al.*, 2014). The effects of gamma irradiation on phenolic contents just after exposure could be explained by the structural modifications due to immediate oxidation, which plays an antioxidant role by reducing the free radicals and the reactive oxygen species (ROS) (Song *et al.*, 2006). At higher radiation doses, the apparent decrease of total phenolic contents might be due to the slight degradation effects on cell composition by gamma irradiation. Antioxidant enzyme activity can be categorised as catalase (CAT), ascorbate peroxidase (APX), and superoxide dismutase (SOD). Increasing trends of CAT in gamma-irradiated tomatoes at 0.5 and 1.0 kGy have been observed (15 and 15.41 µmol/g FW/min, respectively during storage; Kumar *et al.*, 2014). APX activity increased, and was highest at 15 DAI, then declined slightly thereafter in all the treatments except in the combined methods with gamma irradiation. SOD showed opposite trends of decline during storage where control showed the lowest SOD activity, and the highest was observed in the 1 kGy-treated tomato. The lowest antioxidant activity by FRAP assay was obtained for the samples irradiated at 5.7 kGy, and there were no significant differences between these values and the values measured for the control (Guerreiro *et al.*, 2016). The total antioxidant activity, in general, declined for tomatoes under normal storage conditions without any treatments; but during 15 days of storage, it was observed that the activity remained constant in tomatoes irradiated at 1 kGy (Kumar *et al.*, 2014).

5. Consumer perceptions and safety measures

The application of food irradiation on processed food products or fresh fruits and vegetables indeed has room for improvement from its present state. Uncertainties concerning the instrumentation of the procedure, cost-effectiveness, and consumer perception contribute to its approval and application on short-listed fruits and vegetables (Roberts, 2016). Consumers show more enthusiasm to buy irradiated foods by providing satisfactory information about the methods, and their effects, and about 50% or more respondents were eager to buy irradiated food (Eustice and Bruhn, 2013). Consumer acceptance is the most prevailing factor in irradiated food purchasing decisions (Anonymous, 2015) Consumer’s perception of the irradiation of fresh fruits and vegetables is not up to the desired level as they have the notion that food irradiation is a nuclear technology (Maherani *et al.*, 2016). Therefore, the consumers must first be better informed in the effort to overcome the undue reluctance to buy/consume irradiated foods. This can be done by educating the consumers on the non-lethal or non-toxic effects of irradiation as well as irradiation impacts on the trade community due to its operation ease, cost-effectiveness, and safety of irradiated food (Bustos-Griffin *et al.*, 2012). Once the consumers recognised the food security and enhanced shelf life offered by irradiation, a regulatory framework should follow (Bustos-Griffin *et al.*, 2012). In countries that have authorised the application of irradiation and commercialisation of irradiated food products, it is mandatory to include the irradiation symbol in the product labelling (Figure 2; Hallman and Blackburn, 2016).

Figure 2. Radura symbol, which is the universal symbol of irradiation used in product labelling (USFDA, 2014)

The 'Radura' symbol was designed by the Netherlands and features one dot and two leaves in an enclosed circle named (Maherani *et al.*, 2016). 'Radura' originates from the combination of two words; "radurisation" which is derived from radiation, and the Latin word "*durus*" which means durable/lasting, to denote the long-lasting or shelf-life extension of food commodities. The USFDA requires that all irradiated foods be labelled with the 'Radura' symbol along with a declaration "Treated with Radiation" or "Treated by Irradiation" (USFDA, 2016). A recent survey study was conducted on US consumers and found that 61% (n = 484) of participants considered the 'Radura' symbol as an assurance of quality, and showed the eagerness to purchase irradiated foods, while only 5.5% of participants showed no interest to purchase irradiated foods as they considered the 'Radura' symbol as a warning (Follett, 2014).

6. Limitations and recommendations

The technical considerations to extend the future commercial application of gamma irradiation on fresh fruits and vegetables, especially tomatoes will depend on the cost, consumer acceptance, and solution of logistic problems related to handling and treating a large number of commodities. Apart from the consumer perception of irradiated foods, the most important constraints to the application of gamma irradiation are the lack of national/international authenticated regulatory framework, and the lack of infrastructural and gamma source facilities. The logistic problems can be solved by the bilateral commitments between the exporting and importing countries that are interested in irradiated foods. Due to the different geographical situations, Asia is the most important and major manufacturer of all types of fruits and vegetables especially tomatoes in the world, and Asia's environmental conditions are conducive to postharvest losses. Another important constraint is to establish the most efficient dose rates for different commodities, and the combination of one or more preservation techniques including lower doses of irradiation (Follett and Wall, 2013). Extensive research work is essential to assess the combination of various treatments with gamma irradiation, such as modified atmospheric conditions to reduce the cost of postharvest management (Follett and Wall, 2013). They found that many suppliers and retailers are unenthusiastic to take the 'Radura' symbol on irradiated fruits and vegetables due to their misperception that irradiation involves nuclear techniques.

7. Conclusion

Tomato is climacteric in nature, and complex biological modifications correlate with its physiology; respiration rate, total phenolic content, pigment, antioxidant enzyme activity, total antioxidant activity, and ethylene production. The changes in the amounts and the activities of the antioxidants following irradiation may be responsible for interfering with many other physicochemical changes, which facilitate its delayed ripening or softening and ultimately extend its shelf life. Gamma irradiation offers a residue-free non-thermal killing step that has significant potential for fresh fruits and vegetables, and fresh-cut produce like tomato and can be an integral part of the Good Agricultural Practices (GAP), Good Management Practices (GMP), and Good Hygienic Practices (GHP). Gamma irradiation at lower doses (0.5-2.5 kGy) has a vital role in maintaining the microbial and sensory quality of fresh tomatoes. Wide-ranging food commodities including fresh fruits and vegetables are available in the markets, thus presenting both challenges and opportunities for the producers, processors, and consumers in the application of gamma irradiation. Process validation including production methods, pre-cooling, sorting, grading methods, storage conditions, and the market situation could identify the suitable venues at which irradiation can be employed. Ultimately, gamma irradiation plays an important role in the postharvest management of fresh tomatoes as safe and high-quality products with extended shelf life. Furthermore, gamma irradiation can also be used as a short-term treatment to overcome the concerns of long-duration storage of highly perishable commodities such as tomatoes using methyl bromide which is considered an ozone-depleting chemical with impacts towards greenhouse effect.

Conflict of interest

The authors declared no conflict of interest

Acknowledgement

The present work was financially supported by the Bangladesh Agricultural Research Council (BARC) through the National Agricultural Technology Programme-Phase II (NATP-2), and Universiti Putra Malaysia.

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