Effect of ultraviolet irradiation on postharvest quality and composition of tomatoes: a review

Asanda Mditshwa¹ · Lembe Samukelo Magwaza² · Samson Zeray Tesfay¹ ·
Nokwazi Carol Mbili³

Revised: 31 May 2017 / Accepted: 10 August 2017 / Published online: 28 August 2017
© Association of Food Scientists & Technologists (India) 2017

Abstract Ultraviolet (UV) irradiation has recently emerged as a possible alternative to currently used postharvest phytosanitary treatments. Research has also highlighted other benefits associated with UV irradiation in postharvest technology. This review presents the effects of UV irradiation on postharvest and nutritional quality of tomatoes. The application of UV irradiation on tomatoes is discussed including its effect on biological (respiration rate, ethylene production and microbial growth), physico-chemical (firmness, colour, total soluble solids and titratable acidity) and nutritional (vitamins, carotenoids, phenolic and antioxidants) quality. UV-treated tomatoes have shown resistance to microbial growth and decay. Although UV irradiation reduces the loss of vitamin C during storage, the loss of vitamin E remains a concern. UV treatments lead to higher antioxidant capacity, flavonoids and phenolic content. UV irradiation significantly reduced carotenoids in certain cultivars. Based on the literature reviewed, the success of UV irradiation treatments is cultivar-dependent. While improved retention of

phytochemicals has been reported in UV-C treated fruit, increased losses have been reported in certain cultivars. Research efforts on the development of cultivar-specific UV irradiation protocols are warranted. The effect of harvest maturity and seasonal differences in the efficacy of UV treatments is required to be investigated.

Keywords Tomatoes · Postharvest · Quality · Ultraviolet · Irradiation

Introduction

Tomato (*Solanum lycopersicum*), consumed raw or processed, is globally one of the most important vegetables. Several cultivars exhibiting genetic diversity in terms of colour, shape and size as well as taste are used in different parts of the world. Tomato is a rich source of nutrients and secondary metabolites including flavonones, phenolics, vitamin C and E, β -carotene, lycopene and organic acids (Giovanelli and Paradiso 2002). Magnesium, sodium, iron, phosphorus and potassium are some of the minerals found in tomatoes (Kumar et al. 2014). High tomato consumption is strongly linked to a significant proportion of antioxidant in the diet. Epidemiological studies have demonstrated that high tomatoes consumption, the most common source of lycopene, is associated with the anti-inflammatory activity, reduced the risk of certain types of cancers and liver injury (Seren et al. 2008).

Although tomatoes are highly nutritious and tasty, the shorter shelf-life and postharvest quality deterioration immediately after harvest is the major problem affecting tomato producers. This is a major setback for the distribution and marketing of the fresh produce, particularly to distant markets. Since tomatoes cannot be stored for a long

✉ Asanda Mditshwa
mditshwa@ukzn.ac.za; amditshwa@gmail.com

¹ Department of Horticultural Science, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3201, South Africa

² Department of Crop Science, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3201, South Africa

³ Department of Plant Pathology, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3201, South Africa

time, farmers are often forced to reduce prices, even below the cost of production in certain parts of the world (Kumar et al. 2014). Postharvest changes responsible for quality loss and reduced shelf-life in tomatoes are shown in Fig. 1. The accumulation of reactive oxygen species, microbial growth, cell wall degrading enzymes and higher respiration rate are the prominent changes leading to a quality loss in tomato fruit. These changes lead to texture loss and weight loss, physiological disorders and decay. Although postharvest treatments such as heat and chemical treatments are used in prolonging the shelf-life and maintaining the quality of tomatoes, they are not effective in inhibiting microbial growth (Mohácsi-Farkas et al. 2014). The higher incidence of foodborne illnesses prompted the development of new and reliable postharvest treatments ensuring food safety of both fresh and fresh-cut produce.

Various chemical treatments are used in maintaining postharvest quality and prolonging the shelf-life of tomatoes. However, some of the chemical treatments are not effective in eliminating microbial growth during storage. Studies by Guillén et al. (2006, 2007) on the postharvest application of 1-methylcyclopropene (1-MCP) have demonstrated superior external and organoleptic quality compared to untreated fruit. Calcium chloride is another chemical treatment that has been demonstrated to improve microbial and physicochemical properties of tomatoes (Prakash et al. 2007). However, both 1-MCP and calcium chloride are synthetic chemicals and some markets, especially lucrative organic retailers, refuse to accept fruit exposed to such treatments. For processed tomato products, thermal processing and olive leaf extracts have been used

to maintain quality and prolong the shelf-life (Ganje et al. 2016; Jafari et al. 2016, 2017). For instance, Jafari et al. (2017) reported higher vitamin C and total phenolic retention in thermal processed tomato juice. The use of olive leaf extract has also been shown to extend the shelf-life of tomato paste (Ganje et al. 2016). Gamma irradiation at less than 50 kGy, as approved by Food and Drug Administration, is another effective postharvest treatment used in tomatoes (Khalaf et al. 2014). For instance, studies by Adam et al. (2014) showed reduced weight loss, respiration rate and delayed softening in gamma irradiated tomatoes. Reduced microbial count has also been reported in gamma irradiated tomatoes. However, high firmness loss has been reported at higher dosage of gamma irradiation (Prakash et al. 2002).

The loss of nutrients in irradiated fresh produce has been shown to be comparable to conventional postharvest treatments such as hot water dips or chemicals (Shinonaga et al. 1996). Thus, food irradiation technology was initially established as a safe, cheap and clean procedure for eliminating pathogens during storage (Aleksieva et al. 2009; Charles and Arul 2007). Recently, the potential of irradiation as the postharvest treatment of fruits and vegetables has received attention from researchers. There are three types of UV irradiation, UV-A (400–315 nm), UV-B (315–280 nm) and UV-C (280–100 nm). UV-C irradiation is commonly used in sterilizing food products to control foodborne diseases. A considerable amount of research has been conducted on the potential of ultraviolet irradiation in prolonging the shelf-life and maintaining the quality of tomatoes. Given the increasing usage of irradiation in

Fig. 1 Postharvest changes responsible for the quality loss in tomato fruit

tomatoes, there is a need for better understanding of its effect on overall fruit quality. Despite the importance of UV-C irradiation on tomato postharvest quality, there is currently no review on the subject. Therefore, the aim of this review is to assess the effect of UV-C irradiation on postharvest quality of tomato. Additionally, research gaps for future consideration will be highlighted.

Effect of irradiation on biological parameters

Respiration

Respiration is one the main metabolic determinants of tomato quality if this process is not controlled, postharvest quality significantly deteriorates. It is generally accepted that the loss of postharvest quality is proportional to the respiration rate during storage. Thus, postharvest treatments should be aimed at retarding respiration rate during cold-chain and distribution. Fewer studies have studied the effect of irradiation on the respiration rate of tomato (Table 1). For instance, Cote et al. (2013) showed that UV-C irradiation has no effect on respiration rate. In contrast, Vunnam et al. (2014) reported that UV-C treated cherry tomato had highest respiration rate compared to the control treatment and fruit stored in modified atmospheres (MAP). The reduced cell wall degradation of the pericarp following irradiation treatment (Bu et al. 2013) could explain the low respiration rate in irradiated tomatoes. Clearly, although

there is a considerable amount of research on the effect of irradiation on postharvest quality of tomato, very few researchers have studied the respiration rate.

Ethylene production

Ethylene is widely known to regulate many events related to development in plants and it often expressed in response to oxidative stress. At postharvest, ethylene excessive production is linked to the deterioration of fruit quality, as a result, chemical treatments such as 1-Methylcyclopropene (1-MCP) are used to suppress its production. Few studies have established the influence of irradiation on ethylene production (Table 1). For instance, Severo et al. (2015) reported that, although ripening was significantly delayed, UV-C treatment (3.7 kJ m^{-2}) reduced ethylene production in ‘MicroTom’ tomatoes during a 12-day storage at 21°C . Similarly, exposing ‘Zhenzhu’ cherry tomatoes to 4.2 kJ m^{-2} before storage at 18°C for 35 days reduced ethylene production (Bu et al. 2011). The delayed ripening process could be linked to the activation of ethylene response factor (ERF) transcripts acting as regulators of metabolic pathways during ripening (Severo et al. 2015). On the other hand, Bu et al. (2013) argued that ethylene regulates the expression of genes (*PME 2.1*, *Cel 1*, *PG cat* and *Exp 1*) encoding cell wall degrading enzymes leading to delayed ripening. However, both of these hypotheses have not yet been investigated.

Table 1 Studies reporting the effect of ultraviolet and gamma irradiation on biological parameters of tomato

Parameter	Cultivar	Radiation dose (kJ m^{-2})	Key findings	References
Respiration	‘Elpida’	4	No effect	Cote et al. (2013)
	Cherry tomato	3.7	Higher respiration rate compared to control or MAP treatment	Vunnam et al. (2014)
Ethylene	‘MicroTom’	3.7	Low ethylene production	Severo et al. (2015)
	‘Zhenzhu’	4.2	Irradiation reduced ethylene	Bu et al. (2013)
	‘Flavortop’	3.7	UV-C treatment increased ethylene production twice as high compared to untreated fruit	Tiecher et al. (2013)
Microbial growth and decay	‘Trust’	3.7	Resistance to <i>Botrytis cinerea</i>	Charles et al. (2009)
	‘Mecano’	8	UV-C treated fruit had resistance to <i>Penicillium digitatum</i> spores	Obande et al. (2011)
	‘Grape’	0.6–6.0	Inhibited <i>Escherichia coli</i> and <i>Salmonella enterica</i>	Mukhopadhyay et al. (2014)
	‘Better Boy’, ‘Floradade’	3.6	Had 53% inhibition of <i>Rhizopus</i> soft rot	Stevens et al. (2004)
	‘Elpida’	4	Decay was significantly reduced	Cote et al. (2013)

Microbial growth and decay

Postharvest decay induced by microorganisms such as *Rhizopus stolonifer* (Ehrenb.: Fr.), *Alternaria alternata* (Fr.: Fr.) Keissl. and *Botrytis cinerea* (Pers.: Fr) during postharvest handling and distribution is a serious problem in tomatoes (Charles et al. 2009; Obande et al. 2011; Stevens et al. 2004). There has been considerable research on the influence of ultraviolet irradiation on microbial growth and decay in tomato fruit (Table 1). Studies by Obande et al. (2011) showed that UV-C treatment at the dosage of 8 kJ m^{-2} significantly inhibited the growth of *Penicillium digitatum* during a 16-day storage at 16°C . Mukhopadhyay et al. (2014) indicated that UV-C treatment could be used for fresh produce sanitization. In their study, UV-C treatments of $0.60\text{--}6.0 \text{ kJ m}^{-2}$ successfully inhibited *Escherichia coli* and *Salmonella enterica* pathogens on tomatoes stored for 25 days at 5°C . *E. coli* and *S. enterica* are responsible for foodborne illnesses, the ability of UV-C to inhibit these contaminating microbial species should be exploited by producers. Stevens et al. (2004) conducted a study on the effect of UV-C irradiation on the decay of ‘Better Boy’ and ‘Floradade’ tomatoes. Their results showed a significant reduction of decay in UV-C treated fruit. After 9 days of storage at 20°C , Cote et al. (2013) reported that untreated fruit had 23% decay whilst UV-C treated fruit had 8% decay. Interestingly, higher UV intensity was more effective in reducing decay. Similarly, UV-C treated ‘Trust’ tomatoes were more resistant to gray mold decay compared to the untreated fruit (Charles et al. 2008). It could be argued that pathogenesis-related proteins such as β -1,3-glucanase with glucanohydrolase activities induced by UV-C treatment are involved in the mechanism of disease resistance observed in UV-C treated tomatoes (Charles et al. 2009). The increasing demand for fresh tomatoes coupled with highly publicized food contamination cases requires improved postharvest technologies. This above literature collectively shows that postharvest ultraviolet irradiation can be used as an effective and environmentally friendly postharvest treatment to ensure food safety and overall quality of quality tomatoes.

Effect of irradiation on physico-chemical quality

The influence of ultraviolet irradiation on physico-chemical quality parameters such as firmness, colour and weight have been reported by different researchers in several tomato cultivars as summarized in Table 2.

Firmness

Firmness is an important quality parameter in tomato fruit, its loss is easily noticeable during postharvest handling.

Contrasting findings have been reported on the effect of irradiation on the firmness of tomato fruit (Table 2). Bu et al. (2013) compared the firmness of UV-C irradiated and non-irradiated cherry tomatoes and reported better firmness retention in UV-C treated fruit after 35 days of storage at 18°C . Similarly, higher firmness retention in UV-C irradiated ‘Mecano’ tomatoes has been reported (Obande et al. 2011). However, reduced firmness following irradiation treatment has also been reported. For instance, Castagna et al. (2013) and Lui et al. (2009) reported that UV-C irradiation promoted firmness loss in ‘Money Maker’ and ‘Red Ruby’ tomatoes during storage. These contrasting findings may indicate that cultivars respond differently to UV-C irradiation.

In an attempt to explain higher firmness retention, Bu et al. (2013), using transmission electron microscopy, demonstrated that UV-C reduces cell wall degradation of the pericarp. These authors also noted that the cell wall and middle lamella of UV-C treated fruit were still densely arranged, however, the non-irradiated fruit had shrunk cell wall which was separated from the plasma membrane (Fig. 2). Additionally, UV-C has been shown to significantly inhibit cellulase, polygalacturonase and pectinmethylesterase activities, the key cell wall degrading enzymes, resulting in higher firmness retention (Bu et al. 2013). The inhibition of mRNA expression of *PM2.1* and *Cell* in UV-C treated fruit coincided with reduced pectinmethylesterase and cellulase activities showing their possible involvement in inhibiting the activities of cell wall degrading enzymes and fruit firmness (Bu et al. 2013). More research is required to study the effect of irradiation on firmness, moreover, the possibility of combining irradiation with MAP should also be evaluated.

Colour

The potential of irradiation to delay colour development in tomato has been extensively studied (Table 2). Most studies have shown that UV-C irradiation significantly delays the onset of red colouration in tomato fruit. For instance, Bu et al. (2013) demonstrated that exposing ‘Zhenzhu’ tomatoes to 4.2 kJ m^{-2} retarded colour development during storage at 18°C for 35 days. Obande et al. (2011) also reported delayed degreening in ‘Mecano’ tomatoes exposed to 3 or 8 kJ m^{-2} before storage. However, studies on UV-B at 1.1 kJ m^{-2} showed accelerated colour development during storage of ‘Tayfun F1’ tomatoes (Kasim and Kasim 2015). On the other hand, Castagna et al. (2013) reported that exposing ‘Money Maker’ tomatoes to UV-B at 6.08 kJ m^{-2} has no effect on colour development. These reports suggest that, compared to UV-B irradiation, UV-C is more effective in delaying colour

Table 2 The effect of ultraviolet and gamma irradiation on physico-chemical quality of tomatoes

Parameter	Cultivar	Radiation dose (kJ m ⁻²)	Key findings	References
Firmness	Cherry tomato	3.7	UV-C and control treatment had the similar fruit firmness	Vunnam et al. (2014)
	‘Zhenzhu’	4.2	Firmness was better maintained in UV-C treated fruit compared to control treatment	Bu et al., 2013
	‘Mecano’	3 or 8	Firmness was higher in treated fruit compared to control treatment	Obande et al. (2011)
	‘Grape’	0.6–6.0	UV-C treatment had no effect on firmness	Mukhopadhyay et al. (2014)
	‘Money maker’	6.08	UV-B increased firmness loss during storage compared to control treatment	Castagna et al. (2013)
	‘Red Ruby’	13.7	The treatment significantly reduced firmness compared to untreated fruit	Liu et al. (2009)
	‘Flavortop’	3.7	UV-C treated fruit had higher firmness than untreated fruit	Tiecher et al. (2013)
	‘Better Boy’ and ‘Floradade’	3.6	UV-C treated fruit was firmer compared to untreated fruit	Stevens et al. (2004)
	‘Elpida’	4	UV-C treatment had higher firmness retention compared to control treatment	Cote et al. (2013)
Colour	Cherry tomato	3.7	UV-C treated and control treatment had the same colour after storage	Vunnam et al. (2014)
	‘MicroTom’	3.7	Delayed colour development	Severo et al. (2015)
	‘Mecano’	3 or 8	Delayed colour development in green tomatoes	Obande et al. (2011)
	‘Grape’	0.6–6.0	UV-C treatment had no effect on colour	Mukhopadhyay et al. (2014)
	‘Money maker’	6.08	UV-B had no effect on colour development	Castagna et al. (2013)
	‘Red Ruby’	13.7	The treatment delayed colour development	Liu et al. (2009)
	‘Flavortop’	3.7	UV-C delayed degreening during storage	Tiecher et al. (2013)
	‘Elpida’	4	Treated fruit had lower colour development	Cote et al. (2013)
	‘Zhenzhu’	4.2	The UV-C treated fruit developed a pink-red color in contrast to the normal orange-red color of control fruit.	Bu et al. (2013)
	‘Tayfun F1’	1.1	UV-B irradiation accelerated the color development in tomatoes.	Kasim and Kasim (2015)
TSS and TA	‘Tayfun F1’	1.1	UV-B irradiation had no effect on TSS	Kasim and Kasim (2015)
	Cherry tomato	3.7	No significant difference between UV-C treated and control treatment	Vunnam et al. (2014)
	‘Red Ruby’	13.7	The treatment had no effect on TSS	Liu et al. (2009)
	‘Elpida’	4	UV-C treatment had no effect on TSS whilst TA was slightly reduced	Cote et al. (2013)
Weight	Cherry tomato	3.7	The treatment had no effect on weight loss	Vunnam et al. (2014)
	‘Elpida’	4	UV-C treatment significantly reduced weight loss	Cote et al. (2013)

development and ripening of tomatoes. The reduced chlorophyll degradation (Bu et al. 2013) and lycopene content (Jagadeesh et al. 2011) in UV-C treated tomato could be directly linked delayed onset of red colouration.

The higher lycopene to β -carotene ratio, as a result of lower β -carotene content, could be responsible for the altered color phenotype in UV-C treated fruit when compared to the control treatment (Bu et al. 2014).

Fig. 2 Transmission electron micrographs of untreated **a** and UV-C treated **b** cherry tomato after 30 days of storage. CW: cell wall (Adopted from Bu et al. 2013)

Total soluble solids and titratable acidity

Total soluble solids (TSS) and titratable acidity (TA) are important parameters influencing the flavour of tomatoes. The effect of irradiation on TSS and TA is shown in Table 2. Studies have demonstrated that UV-B and UV-C has insignificant influence on TSS of tomatoes (Kasim and Kasim 2015; Liu et al. 2009; Vunnam et al. 2014). Cote et al. (2013) reported that although exposing ‘Elpida’ tomatoes to 4 kJ m^{-2} had no effect on TSS, the treatment slightly reduced TA. It should be noted that most studies on UV-C only reported TSS, however, TA has received little attention. Magwaza and Opara (2015) indicated that TSS/TA ratio is a reliable indicator of fruit sweetness. Moreover, TSS/TA is strongly linked to consumer organoleptic perception of sweet and sour fruit compared to only TSS or TA separately (Hamadziripi et al. 2014). It is, therefore, crucial that future studies on irradiation measure the TSS/TA ratio and its relationship with sensory attributes.

Weight loss

Tomatoes are usually sold on weight basis, weight loss negatively affect prices. Therefore, it is crucial to examine the effect of postharvest technologies on weight loss during storage. The effect of irradiation on weight loss is reported in Table 2. Both UV-C (Cote et al. 2013) and gamma irradiation (Adam et al. 2014) have been reported to significantly reduce weight loss of tomatoes. Future studies should examine the effect of MAP and irradiation on weight loss. Such postharvest treatment combination may significantly reduce weight loss of tomatoes.

Effect of irradiation on shelf-life

Fresh tomatoes have a very poor shelf life and this is a major challenge for the producers. This often forces farmers to sell their produce at reduced prices (Kumar et al. 2014). Jagadeesh et al. (2011) indicated that UV-C is one of the environmentally friendly postharvest treatments to prolong the shelf-life and preserve quality of horticultural crops. Although UV-C irradiation was initially established to control food pathogens, recent research has demonstrated its effectiveness in extending the shelf-life of tomatoes and other horticultural produce. Severo et al. (2015) reported that, in addition to high accumulation of phenolic compounds, UV-C treated tomatoes had longer shelf-life compared to the untreated fruit. Delayed ripening and prolonged shelf-life has also been reported in ‘Flavor-top’ tomatoes (Tiecher et al. 2013). The authors hypothesized that increased polyamine accumulation by UV-C treatment contributes to the longer shelf-life of tomatoes. Studies by Liu et al. (1993) demonstrated that UV-C doses of 1.3 to 40 kJ m^{-2} reduce black mold, gray mold, Rhizopus soft rot and also extend the overall shelf-life of tomatoes. Pinheiro et al. (2015) nicely demonstrated the effect of UV-C treatment on the shelf-life of tomatoes. In their study, UV-C treated tomatoes had shelf-life of 15 days compared to 9 days for untreated fruit. Recent research has demonstrated the response of tomatoes to UV-C treatment is highly influenced by harvest maturity (Liu et al. 1993). Charles et al. (2016) reported that tomatoes harvested at breaker stage are more responsive to UV-C treatments compared to green or fully ripe fruit. This shows that physiological attributes at the time of harvest must be taken into consideration before treatment.

Use of irradiation in processed tomato products

Processed tomato products have recently received high market demand due to busy lifestyles of the consumers. However, due to physical stress such as peeling and slicing imposed to the produce during processing, the product becomes more perishable than the intact fruit. Recent research has demonstrated the effectiveness of UV-C treatment in preserving tomato products including fresh-cut produce. For instance, Bhat (2016) studied the effect of UV-C on the quality of tomato juice. Exposing tomato juice to UV-C for 60 min resulted to higher antioxidant activity and phenolic content whilst ascorbic acid was notably reduced. Additionally, microbial analysis showed lower total plate and mould count in UV-C treated juice compared to the untreated juice. Studies by Kim et al. (2008) on the use of UV-C as a sanitizing treatment on fresh-cut tomatoes also reported reduced development of microbial growth. High phenolic content and delayed vitamin C degradation was also reported in UV-C treated fruit compared to the untreated fruit. The research is clearly limited, the potential use of UV-C as a non-thermal method for food preservation warrants further research.

Effect of irradiation on nutritional and antioxidant quality

Tomatoes are an important supplier of vitamins and antioxidants, therefore, it is important to understand the effect of postharvest irradiation treatments on nutritional quality. There has been a considerable research on the influence of ultraviolet irradiation on nutritional quality. Studies have shown that irradiation significantly affects vitamin content (Charles et al. 2016; Jagadeesh et al. 2011; Severo et al. 2015), phenolics and flavonoids (Castagna et al. 2014; Maharaj et al. 2014), antioxidant capacity (Bravo et al. 2012; Liu et al. 2012) as well as carotenoids (Bu et al. 2014; Pizarro and Stange 2009) of tomato fruit.

Vitamins

The effect of irradiation on vitamins such as ascorbic acid (vitamin C) and tocopherols (vitamin E) was described by different authors in several tomato cultivars and are summarized in Table 3. Liu et al. (2012) studied ascorbic acid in UV-C irradiated ‘Zhenfen 202’ tomatoes (0, 2, 4, 8, and 16 kJ m⁻²) during cold storage at 14 °C for 35 days. The authors reported better ascorbic acid retention in samples irradiated at 4 and 8 kJ m⁻², revealing higher degradation in non-irradiated samples. Although the mechanism of action used by irradiation is not well understood, it could be hypothesized that very high irradiation intensity (16 kJ m⁻²) could be damaging to the membrane, leading

to increased oxidation of ascorbic acid. However, further research is required to validate this hypothesis. Jagadeesh et al. (2011) and Charles et al. (2016) also reported higher ascorbic acid content in irradiated tomatoes compared to the non-irradiated fruit. It should be noted that increased ascorbic acid loss following irradiation has also been reported (Maharaj et al. 2014). In relation to ascorbic acid, it could be argued that tomato cultivars respond differently to irradiation treatments.

Tocopherols, the isoforms of vitamin E, have significant health benefits. Fewer studies have examined the evolution of tocopherols in UV-C treated tomatoes. Severo et al. (2015) demonstrated that δ -tocopherol is considerably lost in ‘MicroTom’ tomatoes irradiated at 3.7 kJ m⁻² during a 12-day storage at 21 °C. The authors did not measure δ -tocopherol and γ -tocopherol levels. Maharaj et al. (2014) studied the effect of UV-C irradiation on these vitamins in the exocarp of ‘Capello’ tomatoes. Their results showed that α -tocopherol, a predominant tocopherol isomer, is significantly lost in irradiated fruit compared to non-irradiated fruit. At 7 days of storage, 24.4 kJ m⁻², non-irradiation and 3.7 kJ m⁻² had a α -tocopherol content decline of 7, 3.7 and 2.3 fold, respectively. The authors argued that the higher α -tocopherol levels in the control treatment could be linked to ripening while on the other hand UV-C probably altered chloroplast membrane leading to reduced α -tocopherol levels. This hypothesis should be tested, and strategies that could be employed in reducing the loss of tocopherols in irradiated fruit should be investigated.

Phenolics, flavonoids and antioxidant capacity

Phenolic, flavonoids and antioxidants are important in tomatoes, mainly for their nutritional quality. Studies have shown that UV-C irradiation has great influence on the phenolic content of tomatoes (Table 3). Jagadeesh et al. (2011) investigated the effect of 3.7 kJ m⁻² and storage time of 10, 20 and 30 days on phenolic content of ‘RK-453’ tomatoes. The irradiated fruit had higher phenolic content compared to non-irradiated fruit. The authors reported that storage had an insignificant effect, however, irradiation was the major contributor to higher phenolic content. Similarly, ‘Capello’ tomatoes exposed to 3.7 and 24.4 kJ m⁻² had higher total phenols compared to the untreated fruit (Maharaj et al. 2014). Higher flavonoid and flavonol concentrations have also been reported in irradiated ‘Money Maker’ and ‘High pigment-1’ tomatoes (Castagna et al. 2014). In an attempt to elucidate the mechanism of UV treatments, Strack (1997) indicated that UV light triggers the accumulation of UV-light absorbing flavonoids and other phenolic compounds. On the other hand, (Tomás-Barberán and Espin 2001) reported that the higher phenolic content in UV treated fruit could be

Table 3 Studies reporting effects of ultraviolet and gamma irradiation nutritional and antioxidant quality of tomatoes

Parameter	Cultivar	Radiation dose (kJ m ⁻²)	Key findings	References
Vitamins	‘RK-453’	3.7	Ascorbic acid was better retained in UV-C treated fruit compared to control treatment	Jagadeesh et al. (2011)
	‘Zhenfen 202’	2, 4, 8, and 16	Fruit exposed to 4 and 8 kJ m ⁻² had better ascorbic acid content	Liu et al. (2012)
	‘MicroTom’	3.7	Fruit treated with UV-C showed lower accumulation of δ -tocopherol	Severo et al. (2015)
	‘Money Maker’	6.08	Treated fruit had higher ascorbic acid content compared to untreated fruit	Castagna et al. (2013)
	‘High pigment-1’	6.08	UV-B treatment had insignificant effect on ascorbic acid content	Castagna et al. (2013)
	‘Capello’	3.7 and 24.4	α -tocopherol and ascorbic acid content were reduced by UV-C treatment	Maharaj et al. (2014)
	‘Balzamo’, ‘Clermont’, ‘Lorenzo’, ‘Makari’, and ‘Trust’	3.7	Higher ascorbic acid was found in treated fruits	Charles et al. (2016)
Phenolics and flavonoids	‘RK-453’	3.7	Higher phenolic content was found in UV-C treated fruit	Jagadeesh et al. (2011)
	‘Zhenfen 202’	2, 4, 8, and 16	4 and 8 kJ m ⁻² increased phenolic content and total flavonoids	Liu et al. (2012)
	‘Capello’	3.7 and 24.4	UV-C treated fruit had high total phenolics compared to non-irradiated fruit	Maharaj et al. (2014)
	‘Daniella’	1.0, 3.0 and 12.2	The UV treatments significantly increased the total phenolic content	Bravo et al. (2012)
	‘Flavortop’	3.7	UV-C treatment had no effect on total phenolic content	Tiecher et al. (2013)
	‘Money Maker’ and ‘High pigment-1’	6.08	Treated fruit had higher phenolic, flavonoid and flavonol concentration	Castagna et al. (2014)
Total antioxidant capacity	‘RK-453’	3.7	The treatment did not affect antioxidant capacity	Jagadeesh et al. (2011)
	‘Zhenfen 202’	2, 4, 8, and 16	Exposing fruit to 4 and 8 kJ m ⁻² increased antioxidant activity	Liu et al. (2012)
	‘Daniella’	1.0, 3.0 and 12.2	The UV treatments significantly increased the antioxidant capacity compared to untreated samples	Bravo et al. (2012)
	‘Money Maker’ and ‘High pigment-1’	6.08	Treated fruit had higher antioxidant activity	Castagna et al. (2014)
	‘Elpida’	4.2	Antioxidant capacity was not affected by the UV-C treatments	Cote et al. (2013)
	Cherry tomato	3.7	UV-C treatment increased antioxidant capacity	Vunnam et al. (2014)
Sugars	‘Tayfun F1’	1.12	UV-B treatment had no effect on sucrose content but glucose and fructose were increased	Kasim and Kasim (2015)
	‘Trust’	3.7	Sucrose was higher in treated fruit whilst fructose and glucose was lower	Charles et al. (2016)

Table 3 continued

Parameter	Cultivar	Radiation dose (kJ m ⁻²)	Key findings	References
Carotenoids	‘RK-453’	3.7	UV treatment significantly reduced the lycopene content	Jagadeesh et al. (2011)
	‘Zhenzhu 1’	4.2	UV treatment had no effect on the lycopene content after storage	Bu et al. (2013b)
	‘MicroTom’	3.7	Fruit treated with UV-C showed lower accumulation of lycopene	Severo et al. (2015)
	‘Zhenzhu 1’	4.2	β-carotene was significantly suppressed in UV-C treated fruit	Bu et al. (2013b)
	‘MicroTom’	3.7	Fruit treated with UV-C showed lower accumulation of lycopene	Severo et al. (2015)
	‘Money Maker’	6.08	Treated fruit no effect on both lycopene and β-carotene content	Castagna et al. (2013)
	‘High pigment-1’	6.08	UV-B treatment had insignificant effect on lycopene and β-carotene content	Castagna et al. (2013)
	‘Daniella’	1.0, 3.0 and 12.2	The lycopene content was almost twofold higher compared to control treatment, while β-carotene levels decreased	Bravo et al. (2012)
	‘Red Ruby’	13.7	Concentration of lycopene increased but β-carotene was not affected	Liu et al. (2009)
	‘Flavortop’	3.7	Compared to control treatment, UV-C treated had lower lycopene and β-carotene content	Tiecher et al. (2013)
	‘Elpida’	4.2	The treatment had no effect on lycopene	Cote et al. (2013)

strongly linked to the activation of a number of biosynthetic pathways and key enzymes such as phenylalanine ammonia lyase (PAL), a catalyst for the synthesis of phenolic compounds such as phenylpropanoids, coumarins and flavonoids.

An extensive study was carried out by Lui et al. (2012) on the effect of UV-C on the total antioxidant activity of ‘Zhenfen 202’ tomatoes. The authors used doses of 2, 4, 8, and 16 kJ m⁻², the fruit was stored at 14 °C and 95% RH for 35 days. Higher total antioxidant activity (measured by Ferric reducing power assay) was reported in fruit exposed to 4 and 8 kJ m⁻². In another study, Bravo et al. (2012) monitored the total antioxidant activity on ‘Daniella’ tomatoes exposed to different doses of irradiation (1.0, 3.0 and 12.2 kJ m⁻²). Similarly, treated fruit had higher antioxidant activity compared to the untreated fruit. The higher antioxidant activity in UV-C treated fruit could be strongly linked higher chlorophyll content, a pigment known to possess lipophilic antioxidant properties (Bravo et al. 2012). Correlative studies aimed at obtaining insights on chlorophyll and antioxidant activity following UV-C treatment should be undertaken. Additionally, further research is warranted to understand the effect of UV-C irradiation on genes and enzymes involved in the biosynthesis of antioxidants.

Carotenoids

Tomatoes are an important source of carotenoids such as lutein, lycopene and β-carotene. The characteristic pigmentation of tomato colour is closely related to carotenoids, especially lycopene. The evolution of carotenoids following UV-C irradiation has received considerable attention from researchers. Most studies have demonstrated that carotenoids are significantly reduced in UV-C treated tomatoes (Table 3). For instance, ‘RK-453’ and ‘MicroTom’ tomatoes exposed to 3.7 kJ m⁻² had lower lycopene content after storage compared to non-irradiated fruit (Jagadeesh et al. 2011; Severo et al. 2015). On the other hand, Bravo et al. (2012) and Liu et al. (2009) reported higher lycopene content in ‘Daniella’ and ‘Red Ruby’ tomatoes exposed to UV-C irradiated before storage. It could be argued that the positive effect of irradiation treatments is cultivar-dependent (Castagna et al. 2013). Bravo et al. (2012) linked the higher lycopene content in treated fruit to possible activation of carotene isomerase, an enzyme in lycopene biosynthesis pathway. Low lycopene content in UV-C treated fruit might be related to the conversion of lycopene to β-carotene by lycopene-β-cyclase, a light-mediated process (Pizarro and Stange 2009). The lower lycopene accumulation in UV-C treated tomatoes coincided with reduced *Psy 1*, a major gene

involved in lycopene synthesis (Bu et al. 2014). Although little efforts have been made to examine the effect of harvest maturity on UV-C effectiveness, previous studies have shown that, after the immature green stage, postharvest light treatments are not essential for stimulating lycopene synthesis (Bravo et al. 2012). More studies should be designed to study this relationship.

The UV-C exposure time seems to have an effect on lycopene content of tomatoes. Bravo et al. (2012) monitored the lycopene content in tomatoes exposed to UV-C treatment for 1, 2 and 3 h. The authors demonstrated that the lycopene synthesis was significantly suppressed in tomatoes exposed to UV-C for 12 h. However, fruit exposed for 1 or 3 h had higher lycopene synthesis. To optimise the effect of UV-C irradiated on tomatoes postharvest quality, the optimal exposure time needs to be investigated for all the prominent cultivars. Longer treatment time may affect the enzymatic activities responsible for lycopene synthesis (Bravo et al. 2012). Studies on the effect of irradiation on β -carotene content have shown contrasting results. Insignificant effect of UV-C treatments on β -carotene content has been reported on various tomatoes cultivars (Castagna et al. 2013; Liu et al. 2009). On the contrary, Bu et al. (2014) and Tiecher et al. (2013) reported lower accumulation and final β -carotene content in UV-C treated tomatoes. In an attempt to understand the mechanisms of UV-C treatments in relation to β -carotene, Bu et al. (2014) reported that UV-C treatment significantly reduced expression of *Lcy- β* , a gene involved in β -carotene synthesis. Bravo et al. (2012) suggested the lower β -carotene content in treated fruit could be linked to inhibition of β -cyclase, an enzyme involved in β -carotene synthesis. On the other hand, Tiecher et al. (2013) reported that, although UV-C treatment trigger the accumulation of transcripts carotenoid biosynthesis genes such as *Psy*, *Zds* and *Lcy- β* , it did not result in higher carotenoid accumulation compared to the control treatment.

Conclusion and future prospects

Literature evidence showed that UV treatments have a beneficial effect on postharvest quality of tomatoes. The impact of UV treatments on respiration rate was reported, which highlighted the need for more research as very few studies have examined the respiration rate in UV treated tomatoes. It is highly important that the effect of UV treatment on respiration rate is well understood, this is attributed to the fact that respiration is one of the metabolic determinates of quality in stored tomatoes. Literature evidence also showed that UV treatments inhibit microorganisms such as *Rhizopons stolonifer*, *Alternaria alternata* and *Botrytis cinerea* which are a prevalent problem during postharvest handling and distribution of tomatoes. The ability of UV irradiation to inhibit the growth of *Escherichia coli* and *Salmonella enterica*, which is

responsible for foodborne illnesses, is plausible. The highly publicized food contamination cases and increasing demand for fresh tomatoes require improved postharvest technologies. This review shows that UV irradiation can be used as an effective and environmentally friendly treatment ensuring microbial safety of stored tomatoes.

The study also showed that UV irradiation has a beneficial impact on physico-chemical quality. UV treatment reduced firmness loss and colour development of in tomatoes during storage and handling is highly desired. Although UV irradiation reduces the loss of vitamin C, the increased vitamin E loss remains a concern. Studies focused on reducing vitamin E loss in UV irradiated tomatoes are required. While UV irradiation has been demonstrated to increase antioxidant capacity, flavonoids, carotenoids and phenolic content, and losses in these phytochemicals have been reported in certain cultivars. The fruit response to UV irradiation depends on many factors including cultivar, harvest maturity and season. Treatment time has also been shown to affect phytochemical properties such as lycopene synthesis. Longer exposure time to UV irradiation may negatively affect enzymatic activities responsible for lycopene synthesis. Developing cultivar-specific UV irradiation protocols is, therefore, critical for the successful storage of tomato fruit.

References

- Adam MY, Elbashir HA, Ahmed AHR (2014) Effect of Gamma Radiation on Tomato Quality during Storage and Processing. *Int Res J Biol Sci* 6:20–25
- Aleksieva K, Georgieva L, Tzvetkova E, Yordanov N (2009) EPR study on tomatoes before and after gamma-irradiation. *Radiat Phys Chem* 78:823–825
- Bhat R (2016) Impact of ultraviolet radiation treatments on the quality of freshly prepared tomato (*Solanum lycopersicum*) juice. *Food Chem* 213:635–640
- Bravo S, García-Alonso J, Martín-Pozuelo G, Gómez V, Santaella M, Navarro-González I, Periago MJ (2012) The influence of post-harvest UV-C hormesis on lycopene, β -carotene, and phenolic content and antioxidant activity of breaker tomatoes. *Food Res Int* 49:296–302
- Bu J, Yu Y, Aisikaer G, Ying T (2013) Postharvest UV-C irradiation inhibits the production of ethylene and the activity of cell wall-degrading enzymes during softening of tomato (*Lycopersicon esculentum* L.) fruit. *Postharvest Biol Technol* 86:337–345
- Bu J, Ni Z, Aisikaer G, Jiang Z, Khan ZU, Mou W, Ying T (2014) Postharvest ultraviolet-C irradiation suppressed *Psy* 1 and *Lcy- β* expression and altered color phenotype in tomato (*Solanum lycopersicum*) fruit. *Postharvest Biol Technol* 89:1–6
- Castagna A, Chiavaro E, Dall'Asta C, Rinaldi M, Galaverna G, Ranieri A (2013) Effect of postharvest UV-B irradiation on nutraceutical quality and physical properties of tomato fruits. *Food Chem* 137:151–158
- Castagna A, Dall'Asta C, Chiavaro E, Galaverna G, Rinaldi M (2014) Effect of post-harvest UV-B irradiation on polyphenol profile and antioxidant activity in flesh and peel of tomato fruits. *Food Bioprocess Technol* 7:2241–2250

- Charles MT, Arul J (2007) UV treatment of fresh fruits and vegetables for improved quality: a status report. *Stewart Postharvest Rev* 3:1–8
- Charles MT, Mercier J, Makhoul J, Arul J (2008) Physiological basis of UV-C-induced resistance to *Botrytis cinerea* in tomato fruit: I. Role of pre-and post-challenge accumulation of the phytoalexin-rihshitin. *Postharvest Biol Technol* 47:10–20
- Charles MT, Tano K, Asselin A, Arul J (2009) Physiological basis of UV-C induced resistance to *Botrytis cinerea* in tomato fruit. V. Constitutive defence enzymes and inducible pathogenesis-related proteins. *Postharvest Biol Technol* 51:414–424
- Charles MT, Arul J, Charlebois D, Yaganza E, Rolland D, Roussel D, Merisier MJ (2016) Postharvest UV-C treatment of tomato fruits: changes in simple sugars and organic acids contents during storage. *LWT-Food Sci Technol* 65:557–564
- Cote S, Rodoni L, Miceli E, Concellón A, Civello PM, Vicente AR (2013) Effect of radiation intensity on the outcome of postharvest UV-C treatments. *Postharvest Biol Technol* 83:83–89
- Ganje M, Jafari SM, Dusti A, Dehnad D, Amanjani M, Ghanbari V (2016) Modeling quality changes in tomato paste containing microencapsulated olive leaf extract by accelerated shelf life testing. *Food Bioprod Process* 97:12–19
- Giovanelli G, Paradiso A (2002) Stability of dried and intermediate moisture tomato pulp during storage. *J Agric Food Chem* 50:7277–7281
- Guillén F, Castillo S, Zapata P, Martínez-Romero D, Valero D, Serrano M (2006) Efficacy of 1-MCP treatment in tomato fruit: 2. Effect of cultivar and ripening stage at harvest. *Postharvest Biol Technol* 42:235–242
- Guillén F, Castillo S, Zapata P, Martínez-Romero D, Serrano M, Valero D (2007) Efficacy of 1-MCP treatment in tomato fruit: 1. Duration and concentration of 1-MCP treatment to gain an effective delay of postharvest ripening. *Postharvest Biol Technol* 43:23–27
- Hamadziripi ET, Theron KI, Muller M, Steyn WJ (2014) Apple compositional and peel color differences resulting from canopy microclimate affect consumer preference for eating quality and appearance. *HortScience* 49:384–392
- Jafari S, Jabari S, Dehnad D, Shahidi S (2016) Heat Transfer Enhancement in Thermal Processing of Tomato Juice by Application of Nanofluids. *Food Bioprocess Technol* 1–10
- Jafari S, Jabari S, Dehnad D, Shahidi S (2017) Effects of thermal processing by nanofluids on vitamin C, total phenolics and total soluble solids of tomato juice. *J Food Sci Technol* 54:679–686
- Jagadeesh S, Charles M, Gariepy Y, Goyette B, Raghavan G, Vigneault C (2011) Influence of postharvest UV-C hormesis on the bioactive components of tomato during post-treatment handling. *Food Bioprocess Technol* 4:1463–1472
- Kasim MU, Kasim R (2015) Postharvest UV-B treatments increased fructose content of tomato (*Solanum lycopersicon* L. cv. Tayfun F1) harvested at different ripening stages. *Food Sci Technol (Campinas)* 35:742–749
- Khalaf H, Sharoba A, El Sadani R, El Nashaby FM, Elshiemy S (2014) Antioxidant properties of some extracts from gamma irradiated tomato (*Lycopersicon esculentum* L.) pomace. *Food and Dairy Sci. Mansoura Univ* 5:247–263
- Kim H, Fonseca JM, Kubota C, Kroggel M, Choi J (2008) Quality of fresh-cut tomatoes as affected by salt content in irrigation water and post-processing ultraviolet-C treatment. *J Sci Food Agric* 88:1969–1974
- Kumar M, Ahuja S, Dahuja A, Kumar R, Singh B (2014) Gamma radiation protects fruit quality in tomato by inhibiting the production of reactive oxygen species (ROS) and ethylene. *J Radioanal Nucl* 301:871–880
- Liu C, Cai L, Lu X, Han X, Ying T (2012) Effect of postharvest UV-C irradiation on phenolic compound content and antioxidant activity of tomato fruit during storage. *J Integr Agric* 11:159–165
- Liu J, Stevens C, Khan V, Lu J, Wilson C, Adeyeye O, Kabwe M, Pusey P, Chalutz E, Sultana T (1993) Application of ultraviolet-C light on storage rots and ripening of tomatoes. *J Food Prot* 56:868–873
- Liu L, Zabarar D, Bennett L, Aguas P, Woonton B (2009) Effects of UV-C, red light and sun light on the carotenoid content and physical qualities of tomatoes during post-harvest storage. *Food Chem* 115:495–500
- Magwaza LS, Opara UL (2015) Analytical methods for determination of sugars and sweetness of horticultural products—A review. *Sci Hort* 184:179–192
- Maharaj R, Arul J, Nadeau P (2014) UV-C irradiation effects on levels of enzymic and non-enzymic phytochemicals in tomato. *Innov Food Sci Emerg Technol* 21:99–106
- Mohácsi-Farkas C, Nyíró-Fekete B, Daoud H, Dalmadi I, Kiskó G (2014) Improving microbiological safety and maintaining sensory and nutritional quality of pre-cut tomato and carrot by gamma irradiation. *Radiat Phys Chem* 99:79–85
- Mukhopadhyay S, Ukuku D, Juneja V, Fan X (2014) Effects of UV-C treatment on inactivation of *Salmonella enterica* and *Escherichia coli* O157: H7 on grape tomato surface and stem scars, microbial loads, and quality. *Food Control* 44:110–117
- Obande MA, Tucker GA, Shama G (2011) Effect of preharvest UV-C treatment of tomatoes (*Solanum lycopersicon* Mill.) on ripening and pathogen resistance. *Postharvest Biol Technol* 62:188–192
- Pinheiro J, Alegria C, Abreu M, Gonçalves EM, Silva CL (2015) Use of UV-C postharvest treatment for extending fresh whole tomato (*Solanum lycopersicum*, cv. Zinac) shelf-life. *J Food Sci Technol* 52:5066–5074
- Pizarro L, Stange C (2009) Light-dependent regulation of carotenoid biosynthesis in plants. *Cienc Investig Agrar* 36:143–162
- Prakash A, Manley J, DeCosta S, Caporaso F, Foley D (2002) The effects of gamma irradiation on the microbiological, physical and sensory qualities of diced tomatoes. *Radiat Phys Chem* 63:387
- Prakash A, Chen P, Pilling RL, Johnson N, Foley D (2007) 1% calcium chloride treatment in combination with gamma irradiation improves microbial and physicochemical properties of diced tomatoes. *Foodborne Pathogens Disease* 4:89–98
- Seren S, Lieberman R, Bayraktar UD, Heath E, Sahin K, Andic F, Kucuk O (2008) Lycopene in cancer prevention and treatment. *Am J Ther* 15:66–81
- Severo J, Tiecher A, Pirrello J, Regad F, Latché A, Pech J, Bouzayen M, Rombaldi CV (2015) UV-C radiation modifies the ripening and accumulation of ethylene response factor (ERF) transcripts in tomato fruit. *Postharvest Biol Technol* 102:9–16
- Shinonaga T, Ambe S, Enomoto S, Maeda H, Iwamoto M, Watanabe T, Yamaguchi I (1996) Multitracer study on the behavior of various elements in atmosphere plant-systems. *J Radioanal Nucl Chem* 212(3):163–172
- Stevens C, Liu J, Khan V, Lu J, Kabwe M, Wilson C, Igwegbe E, Chalutz E, Droby S (2004) The effects of low-dose ultraviolet light-C treatment on polygalacturonase activity, delay ripening and *Rhizopus* soft rot development of tomatoes. *Crop Prot* 23:551–554
- Strack D (1997) 10 Phenolic Metabolism. *Plant Biochem* 387
- Tiecher A, de Paula LA, Chaves FC, Rombaldi CV (2013) UV-C effect on ethylene, polyamines and the regulation of tomato fruit ripening. *Postharvest Biol Technol* 86:230–239
- Tomás-Barberán FA, Espin JC (2001) Phenolic compounds and related enzymes as determinants of quality in fruits and vegetables. *J Sci Food Agric* 81:853–876
- Vunnam R, Hussain A, Nair G, Bandla R, Gariepy Y, Donnelly D, Kubow S, Raghavan G (2014) Physico-chemical changes in tomato with modified atmosphere storage and UV treatment. *Journal Food Sci Technol* 51:2106–2112