Scientia Horticulturae 226 (2017) 97–103

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Effects of continuous red light and short daily UV exposure during postharvest on carotenoid concentration and antioxidant capacity in stored tomatoes

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ARTICLE INFO

Keywords:
Lycopene
β-Carotene
Antioxidant activity
LED
Postharvest
Solanum lycopersicum L.

ABSTRACT

Due to their health benefits, high concentrations of antioxidative compounds in vegetables and fruit are important for end-consumers. The aim of this research was to investigate the effects of continuous red light and short periods of daily ultraviolet (UV) radiation on the postharvest quality of green tomatoes. Green tomatoes were exposed for 30 min to UV radiation, continuous red light or a combination of both for up to 20 d. Non-treated (control) fruit ripened within 15 d while fruit exposed to red light and a combination of red light with UV radiation required five days less to reach the same maturity level. In addition, the exposure to red light alone or in combination with UV raised concentrations of lycopene, ß-carotene, total flavonoids and phenolics. This possibility to steer the concentrations of health-promoting antioxidants through light treatments is a safe method to increase fruit quality according to customer wishes and demands.

1. Introduction

Fruit ripening is a complex, genetically programmed process that comprises changes in colour, texture, flavour, and chemical composition (Javanmardi and Kubota, 2006). Tomato is a climacteric fruit and continues to ripen after harvest. The United States Department of Agriculture (USDA) established a colour classification system, which is widely used to differentiate the ripeness of tomatoes (USDA, 2005). The ripening stage of tomato fruit is usually defined on basis of external colour, which changes due to the degradation of chlorophyll and the biosynthesis of lycopene, the most abundant carotenoid (López et al., 2007), as well as ß-carotene, a precursor of vitamin A (Hobson and Grierson, 1993).

The health promoting benefits of tomato and tomato products have mainly been attributed to the significant amount of natural antioxidants, especially lycopene (Ilić et al., 2012). Antioxidants are compounds that can delay or inhibit the oxidation of lipids or other molecules by inhibiting the initiation or propagation of oxidative chain reactions (Velioglu et al., 1998). In the human body, the oxidative metabolism can induce continuous production of free radicals. These highly aggressive compounds can cause permanent cell damage, leading to mutation and possibly cancer in human cells (Choudhary and Walters, 2013).

Lycopene is presently commercialized as a potent antioxidant and fortified nutritional supplement (Kaur and Kapoor, 2008). Epidemiological studies have shown that the increased consumption of lycopene-rich food is associated with lower risk of cancer (Giovannucci, 1999). Furthermore, results suggest that lycopene plays a role in the prevention of different health issues, such as chronic diseases, cardiovascular disorders, digestive tract tumors, and can also inhibit prostate carcinoma cell proliferation in humans (Levy and Sharoni, 2004). In tomatoes, the changes in content, chemical composition, and antioxidative properties during ripening depend on environmental factors such as temperature, light, water availability and nutrient availability (Cano et al., 2003; Jimenez et al., 2002), the agricultural techniques, cultivars, plant growth regulators and ripening stage (Kotíková et al., 2011; Ozgen et al., 2012).

In the past decades, considerable work has been conducted to increase levels of carotenoids in tomatoes through breeding programs or ripening intervention technologies during post-harvest storage, such as additional radiation with different light spectra (Alba et al., 2000; Liu et al., 2003; Rosati et al., 2000). Excessive exposure to UV light causes

Abbreviations: UV, ultraviolet; USDA, The United States Department of Agriculture; NDVI, the Normalised Difference Vegetation Index; NAI, the Normalised Anthocyanin Index; TSS, Total soluble solids; PAR, Photosynthetic Available Radiation; HPLC, high performance liquid chromatography; QAE, quercetin equivalents; TE, Trolox equivalents; ABTS+, 2,2′-azino-bis(3-ethylbenzthiazoline-6-sulphonic acid)

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http://dx.doi.org/10.1016/j.scienta.2017.08.035
Received 13 April 2017; Received in revised form 18 August 2017; Accepted 21 August 2017

stress in plant tissues and stimulates the biosynthesis of defensive secondary metabolites with antioxidant and screening activity. Examples of these compounds include lycopene in tomatoes (Liu et al., 2009) and phenolic compounds in grapes and tomatoes (Cantos et al., 2000; González-Barrio et al., 2009; Jagadeesh et al., 2011; Liu et al., 2009). Moreover, UV-B irradiation is considered being a useful non-chemical way of maintaining postharvest quality and enhancing antioxidant capacity of tomato fruit (Liu et al., 2011). As reported, UV-C exposure in low dose might delay ripening, improve firmness and extend the shelf-life of tomatoes (Stevens et al., 2004).

Red light treatments (5 min of red light with 15 min of far-red light) increased lycopene accumulation 2.3-fold in tomatoes (Alba et al., 2000), indicating that the accumulation of lycopene was controlled by fruit-localised phytochromes. Other studies have shown that red light treatment increases the carotenoid content and red colour of tomatoes, with varying effects on tomato firmness (Lee et al., 1997; Liu et al., 2009). However, no study has examined the effect of red light or UV on the ripening time of tomato fruit. In addition, it is so far unclear how different light treatments can influence antioxidant activity in tomato fruit.

Therefore, the objective of this research was to investigate the potential of continuous red light and short periods of UV radiation to shorten postharvest ripening time and to increase concentrations of lycopene, β-carotene, total flavonoid and phenolic content as well as hydrophilic and lipophilic antioxidant activity in green stage tomatoes during postharvest storage.

2. Materials and methods

2.1. Tomato cultivation

Tomato (*Solanum lycopersicum* L.) fruit of the cultivar Cappricia (RijkZwaan, De Lier, The Netherlands) were harvested from plants cultivated in a commercial-like greenhouse at the Campus Klein-Altendorf research station (University of Bonn, Germany, 50°37′31.6″N 6°59′18.1″E, altitude 600 m). Fruit with calyx were harvested at the green stage 1 of maturity (USDA, 2005), as detailed in section 2.3. In order to restrict potential influences of developmental and environmental factors, one healthy tomato fruit of pre-defined size was harvested from a truss from different plants (always from the same position). Afterwards, tomatoes were placed into plastic trays covered with aluminum foil (30 fruit per tray), ensuring that the fruit did not touch each other. The trays were stored in a custom-built climate chamber for 20 d under constant day/night temperatures (20 °C/19 °C) with variable, day/night temperature-dependent relative humidity (75%/85%).

2.2. Light treatments

For this experiment, four different treatments were used:

1) Darkness (control)
2) Darkness + UV
3) Red light
4) Red light + UV

In treatment 1 (control), tomato fruit were placed in a box and kept in the dark in the same climate chamber, but separated via a cardboard to shield them from the light. For treatment 2 and 4, tomato fruit were additionally irradiated with UV light for 15 min every day in the morning (at 6.15 am) and at night (at 7.30 pm) with UV tubes (UV-XEFL 290BB, Ushio Lighting Inc., Japan). Tomato fruit were exposed to UV light of 4.98 kJ m^{-1} per 30 min per day which is equivalent to a biologically effective UV radiation of 5.53 kJ m^{-1} 30 min per day (UV-BBE = 4.5, UV-CBE = 1.0, UV-ABE = 0.03 per 30 min per day) (Hoffmann et al., 2015). For treatment 3 and 4, the tomato fruit were irradiated with special light emitting diode (LED) modules (Ushio Lighting Inc., Tokyo Japan) installed in the climate chamber. This prototype, optimized for our research purpose, consisted of the following spectrum: 60% UV-B (280–320 nm with a dominant peak at 290 nm), 30% UV-A (320–400 nm), 4% UV-C (200–280 nm) and 6% visible light (400–700 nm) (Hoffmann et al., 2015). The LED settings (intensity and spectral composition) were controlled by the equipment-specific software. The red light was applied for the whole storage period (red light peak at 665 nm) which is equivalent to a Photosynthetic Available Radiation (PAR) of 113 µmol m^{-2} per day (X1-2 SN4962 M RS232 optometer, Gigahertz-Optik GmbH, Germany). All tomato fruit were carefully turned over every day (at 2 pm) to ensure light exposition of both fruit sides.

2.3. Tomato fruit sampling and remittance determinations

Six tomatoes were sampled on harvesting day (day 0) to characterize the quality (stage) at the starting point. External fruit colour was assessed visually according to the Standards for Grade of Fresh Tomatoes established by the United States Department of Agriculture (USDA, 2005). For rating, the following scale was used:

1 = green, 100% green
2 = breaker, a noticeable break in colour with less than 10% of colour other than green
3 = turning, between 10 and 30% red (ish) colour
4 = pink, between 30 and 60% red (ish) colour
5 = light red, between 60 and 90% red
6 = red, more than 90% red

2.4. Remittance analysis

A hand-held spectrophotometer (Pigment Analyzer 1101, Control in Applied Physiology GbR, Germany) was used for non-destructive remittance analyses, including the Normalised Difference Vegetation Index (NDVI, estimating the chlorophyll concentration) and the Normalised Anthocyanin Index (NAI). Three points on each fruit were evaluated every 5 d, and an average NDVI and NAI per tomato fruit was calculated the following way:

$$NDVI = (R780\text{-}R660)/(R780 + R660)$$

$$NAI = (R780\text{-}R570)/(R780 + R570)$$

2.5. Sample preparation for destructive analyses

After the initial harvest, sampling was performed every 5 d (Day 0, 5, 10, 15 and 20). For this purpose, six fruit were randomly chosen from each treatment. After analysis of above-mentioned optical and sensor-based properties, fruit were cut into small pieces and kept at −80 °C for lyophilisation (Gamma 1-16LSC, Christ, Osterode am Harz, Germany). Dried samples were ground and stored in the dark at room temperature until further preparation, extraction procedures and lab analyses.

2.6. Total soluble solids (TSS)

TSS represents an index of soluble solids concentration in fruit. A single drop of juice from homogenated, ground tomato tissue was put on a digital refractometer (Pocket PAL-1, ATAGO, Tokyo, Japan). Results were expressed as%.

2.7. Extraction procedure

The methanolic extraction 80% methanol [PubChem CID: 887] + 1.0% hydrochloric acid ([PubChem CID: 313] [37%, Merck, Germany]) described previously (Ponmozhi et al., 2011) with slight modifications was used for hydrophilic antioxidant activity, total