Postharvest Biology and Technology 108 (2015) 78–85

Contents lists available at ScienceDirect

Postharvest Biology and Technology

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

Effect of postharvest short-term radiation of near infrared light on transpiration of lettuce leaf

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ARTICLE INFO

Article history:
Received 19 February 2015
Received in revised form 7 May 2015
Accepted 19 May 2015
Available online 11 June 2015

Keywords:
NIR
Water loss
Stomatal aperture
ROS

ABSTRACT

We investigated the physiological effects of short-term postharvest near infrared (NIR) radiation on relative transpiration rates, stomatal apertures, and reactive oxygen species (ROS) levels in guard cells on excised young lettuce leaves and on transpiration of leaf lettuce at commercial maturity. When the young leaves were radiated by NIR of wavelengths longer than 850 nm at 100 μmol m^{-2} s^{-1} for short duration (10–60) min, relative transpiration rates during subsequent storage were reduced, but not by visible light radiation and by longer radiation (180 min) of NIR. The reduction in transpiration rates by the short-term NIR radiation was greater at 10 °C than at 25 °C under both dark and light conditions during subsequent storage. The short-term NIR radiation enhanced stomatal closure and ROS accumulation in guard cells of young lettuce leaves. These results indicate that the suppression of transpiration by short-term NIR radiation is likely to be mediated through stomatal closure due to NIR-induced ROS accumulation. The reduction of transpiration by short-term NIR radiation was obtained not only in excised young leaves but also in leaf lettuce at commercial maturity, resulting in keeping freshness. The short-term NIR radiation could be an additional means to extend shelf life of leaf vegetables.

1. Introduction

Light is particularly important to plants as a source of energy for photosynthesis; hence, plants modulate their physiology and morphology according to the surrounding light conditions. Light-mediated responses include various aspects of the plant life cycle, such as germination, phototropism, and stomatal opening (Reed et al., 1993; Blum et al., 1994; Lin, 2000; Wang et al., 2010). Since Darwin's study, both blue light and red light exposure have been known to open the stomata in growing plants (Darwin, 1881; Lin, 2002). Blue light-induced stomatal opening has been reported to be mediated by the blue light receptor phototropins (PHOT1 and PHOT2) and cryptochromes (CRY1 and CRY2) (Wang et al., 2010). It has been demonstrated that red-light induced stomatal opening can be fully reversed by far-red light (700–720 nm) in both orchid and *Arabidopsis*, indicating the presence of a phytochrome-mediated stomatal opening response (Talbott et al., 2002, 2003). Therefore, exposure to far-red light can enhance stomatal closure. Incident red, blue, far-red, and ultraviolet (UV) light elicit subsets of these responses.

Light-emitting diodes (LEDs) have great potential as lighting systems for crop production and postharvest technology because of their small size, long operating lifetime, and wavelength specificity. Because the waveband of LEDs is much narrower than that of the traditional sources of electric lighting, it can provide the specific wavelengths of light for specific objectives (Massa et al., 2008; Yano and Fujiwara, 2012).

Postharvest water loss is an important physiological process that affects the main quality characteristics of fresh fruit and vegetables, such as appearance and texture. As a loss in weight of only 5% can cause fresh produce to lose freshness and appear wilted, water loss is an important parameter to be considered for designing postharvest handling systems (Kader, 1994; Mahajan et al., 2008). Fresh produce is usually stored under dark conditions, even though light radiation is known to retard leaf senescence (Goldthwaite and Laetsch, 1967; Hurng et al., 1986; Gustavo et al., 2013; Costa et al., 2013). In spinach mustard stored under dark conditions, chlorophyll and ascorbic acid contents decreased to

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http://dx.doi.org/10.1016/j.postharvbio.2015.05.010
0925-5214/

20% of initial level in three days at 28 °C (Hosoda et al., 1981). However, postharvest exposure to strong light can increase water loss through transpirational water loss, resulting in reduced shelf life (Kader, 1986). On the other hand, a number of studies have shown that prestorage exposure of fruit and vegetables to UV light was effective in reducing the development of postharvest disease (Turtoi, 2013). For instance, radiation with UV-C light after harvest could extend the postharvest life of 'Karaj' persimmon (Khademi et al., 2013) and 'Tommy Atkin' 'Haden' mangoes (González-Aguilar et al., 2001, 2007) by disease control. Moreover, when used at an optimum level, UV-C light induced an accumulation of phytoalexins that play an important role in disease resistance in tomato fruit and several plants (Rodov et al., 1992; Charles et al., 2008).

Continuous or intermittent illumination has been reported to be effective for preserving leaf quality and chlorophyll and ascorbic contents of spinach mustard (Hosoda et al., 1981). Postharvest radiation with LED lamps at low intensity improved edible quality and tasty constituents in sweet corn (Ohta et al., 2008) and prevented senescence in broccoli (*Brassica oleracea* L.) (Büchert et al., 2010; Ma et al., 2010). Near infrared (NIR) is usually defined as a wavelength ranging from 750 nm to 1400 nm. Physiological responses to NIR radiation between 705 nm and 740 nm via phytochromes in plants have been well studied. The postharvest exposure of potatoes to 730 nm NIR light inhibited its sprouting (Harada and Nakamura, 2010). On the other hand, the effects of wavelengths longer than 740 nm have not been studied because the long wavelengths of far-red radiation are easily absorbed in crops leading to a rise in their temperature. There are few studies on the application of wavelengths longer than 740 nm for postharvest quality control of fresh fruit and vegetables.

NIR spectroscopy has been successfully applied to measure the internal quality attributes of horticultural produce such as peaches, apples, kiwifruits, and 'Nanfeng' 'Satsuma' mandarins (Fujiwara and Honjo, 1995; Slaughter and Crisosto, 1998; Clark et al., 2004; Kawano, 2008; Bobelyn et al., 2010; Liu et al., 2010). However, relatively little work has been conducted on the physiological effects of postharvest NIR radiation on products. In our preliminary trial of postharvest short-term NIR radiation on lettuce, we observed less wilting than that in the non-treated controls, suggesting reduced water loss.

Stomatal apertures are a major pathway for transpiration, accounting for 95% of water loss from plants (He et al., 2006). The physiological effects of light radiation on stomatal behavior during plant growth have been intensively studied. An action spectrum of stomatal opening on the leaves of *Xanthium strumarium* L. indicated that blue light was nearly ten times more effective than red light (Sharkey and Raschke, 1981). At a low quantum flux density, the stomatal opening of *Vicia faba* was activated only in the blue and UV regions, whereas at higher quantum flux density, stomatal opening also responded to red and slightly responded to green light (Hsiao and Allaway, 1973). Furthermore, stomatal opening induced by blue light was inhibited by abscisic acid (ABA) (Murata et al., 2001; Yin et al., 2013), whereas salicylic acid (SA) triggered stomatal closure (Joon-Sang, 1998; Miura et al., 2013). In Arabidopsis, ABA-induced stomatal closure has been shown to be dependent on reactive oxygen species (ROS) production and Ca^{2+} channel activation (Murata et al., 2001).

Most studies on transpiration and stomata physiology have been conducted in growing plants, whereas little attention has been given to postharvest crops. To the best of our knowledge, no report is available specifically on the effects of NIR radiation on water loss and stomatal behavior in postharvest fresh produce. In this study, we investigated the effects of postharvest NIR radiation on excised lettuce leaves to determine the effective wavelength, light intensity, and radiation time required for NIR light from LEDs or a xenon arc lamp to reduce postharvest water loss in lettuce leaf. In addition, stomatal responses and ROS accumulation were studied to understand the physiological mechanism of the postharvest short-term NIR radiation.

2. Materials and methods

2.1. Plant materials

The lettuce (*Lactuca sativa* L. Crispa Group) 'Notip' and 'Cisco' (Hashimoto seed Co., Ltd., Japan) were grown in soilless culture with a bottom irrigation system using Qtsuka-A culture solution (EC = 1.2 ds/m, Otsuka Co., Ltd.) in a growth chamber that was equipped with fluorescent lamps (140 $\mu mol\,m^{-2}\,s^{-1}$, 12-h day and 12-h night, FL40SS W/37, Toshiba). Lettuce leaf of 300–400 mg at the two true-leaf stage, equivalent to that of baby leaf greens, were harvested at 3 weeks after sowing and used for experiments as excised young leaves. For the experiment on leaf lettuce at commercial maturity, 'Notip' lettuce of commercial size (about 20 cm long) was obtained directly from Tokuju plant factory (Tokuju Co.) in Takamatsu city, Japan. Weight before light radiation and after storage was measured and relative transpiration rates were calculated.

2.2. Effects of radiation wavelength, intensity, and duration on transpiration rates of excised young lettuce leaves

2.2.1. Effect of wavelength

Lights of the desired wavelengths, except 1015 nm, were generated using an LED platform. Seven radiation wavelength were tested as follows: blue (peak wavelength (λP)/ $_{\mathrm{fullwidthathalf\text{-}maximum(FWHM)} = 470\,\mathrm{nm}/30}$), green ($\lambda P/_{\mathrm{FWHM}} = 530\,\mathrm{nm}/_{40}$), red ($\lambda P/_{\mathrm{FWHM}} = 660\,\mathrm{nm}/_{20}$), and near infrared ($\lambda P/_{\mathrm{FWHM}} = 730\,\mathrm{nm}/_{30}$, $\lambda P/_{\mathrm{FWHM}} = 850\,\mathrm{nm}/_{40}$, $\lambda P/_{\mathrm{FWHM}} = 940\,\mathrm{nm}/_{50}$, and $\lambda P = 1015\,\mathrm{nm}$). The 1015 nm light was generated by a halogen lamp and pass filters. The spectra used in these experiments are shown in Fig. 1. The excised young lettuce leaves were radiated with lights of various wavelengths at an intensity of 100 $\mu mol\,m^{-2}\,s^{-1}$ for 10 min and then incubated for one day under dark conditions at 98% RH or higher. Non-radiated young lettuce leaves were used as control. All experiment was conducted at 10 °C.

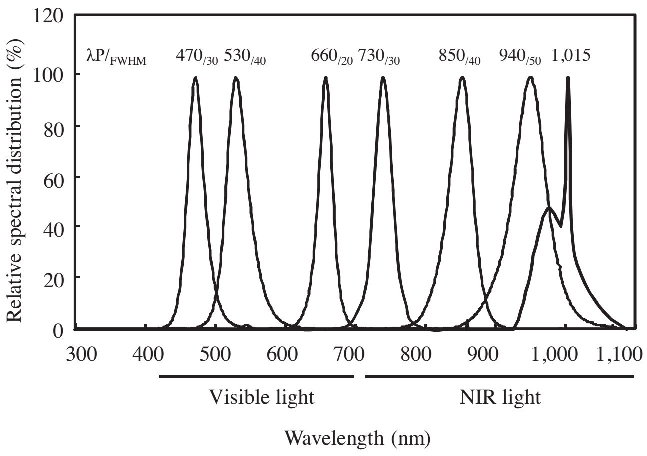

Fig. 1. Spectral distribution of the LED light used in this study. Light source; LED, blue ($\lambda P/_{\mathrm{FWHM}} = 470\,\mathrm{nm}/30$), green ($\lambda P/_{\mathrm{FWHM}} = 530\,\mathrm{nm}/40$), red ($\lambda P/_{\mathrm{FWHM}} = 660\,\mathrm{nm}/20$), near infrared ($\lambda P/_{\mathrm{FWHM}} = 730\,\mathrm{nm}/_{30}$,$\lambda P/_{\mathrm{FWHM}} = 850\,\mathrm{nm}/40$, $\lambda P/_{\mathrm{FWHM}} = 940/50$). Light source; halogen lamp, near infrared ($\lambda P = 1015\,\mathrm{nm}$), $\lambda P/_{\mathrm{FWHM}}$ = peak wavelength (nm)/$_{\text{full width at half maximum (nm)}}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)