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The combined effects of ultraviolet-C irradiation and modified atmosphere packaging for inactivating *Salmonella enterica* serovar Typhimurium and extending the shelf life of cherry tomatoes during cold storage

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A B S T R A C T

The combined effects of ultraviolet-C (UV-C) irradiation, modified atmosphere packaging (MAP), and cold storage temperature on the quality of inoculated (*Salmonella enterica* serovar Typhimurium) and non-inoculated cherry tomatoes were investigated. Based on the inactivation and sublethal injury tests of S. Typhimurium by UV-C irradiation, 2 kJ/m^2 UV-C was selected for the combined treatment. Non-inoculated and inoculated cherry tomatoes were irradiated with 2 kJ/m^2 UV-C and then packaged under two different modified atmosphere conditions (passive and active) and stored for 9 d at 4 and 20 °C. As controls, non-irradiated cherry tomatoes packaged in perforated film bags were stored. When the inoculated cherry tomatoes that were irradiated with UV-C were packaged under an active modified atmosphere (5.3% CO_2 + 5.5% O_2), the S. Typhimurium populations were significantly reduced during storage at 4 °C compared to those of other treatments. Regarding the color, the combination of UV-C and active MAP delayed the change of Hunter b^* and ΔE values in cherry tomatoes during storage at 4 °C. Regardless of treatment and packaging method, the cherry tomatoes stored at 4 °C exhibited a lower decrease of firmness compared to those stored at 20 °C. After 9 d of storage at 4 or 20 °C, there were significant differences in lycopene content and weight loss depending on storage temperature or gas composition in packaging film. Therefore, these results suggest that the combination of UV-C irradiation and active MAP can improve the microbial safety and extend the shelf life of cherry tomatoes during cold storage.

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1. Introduction

Fresh produce is consumed worldwide as an important part of a healthy diet; thus, the preservation of fresh vegetables and fruits is a primary concern of the food industry for both domestic demand and export (Ghate et al., 2013; Sawe, Onyango, & Njage, 2014). In particular, the consumption of tomatoes in raw form in salads, hamburgers, and fresh juices has increased owing to their being a good source for ascorbic acid, carotenoids, and folate, and because of their attractive color (Bu et al., 2014; Muratore, Rizzo, Licciardello, & Maccarone, 2008; Zhao et al., 2010). Several epidemiological studies have reported that regular consumption of tomatoes reduces the incidence of oxidative stress-related diseases including cardiovascular disease and atherosclerosis (Abete et al., 2013; Ahmed, Martin-Diana, Rico, & Barry-Ryan, 2013).

However, foodborne pathogens have been isolated from commercially grown raw vegetables, which can become contaminated during the harvesting, postharvest treatment, storage, or distribution stages (Mahmoud, 2010; Oliveira et al., 2010). The microbial contamination in raw whole and sliced tomatoes has been implicated in *Salmonella* outbreaks (Moreira, Puerta-Gomez, Kim, & Castell-Perez, 2012; Niemira & Boyd, 2013). *Salmonella enterica* serovar Typhimurium is a causative agent of non-typhoid salmonellosis and is known to grow on the surface of tomatoes at temperatures as low as 12 °C (Gurtler et al., 2012). In addition, poor postharvest handling, such as a broken cold chain and unsuitable packaging materials, results in high postharvest losses due to enhanced physiological activities and other metabolic processes that are associated with deterioration of produce. Thus, to meet the market demand for improving microbiological quality and extending the shelf life of fresh tomatoes, microbial growth and storage conditions should be controlled during tomato storage.

Although the most common preservation method for raw vegetables is refrigeration, this is not sufficient to kill microorganisms, but rather simply retards their growth during storage. Thus, there is a need for the development of a combined treatment for raw vegetables that will be effective in reducing microbial contamination without damaging food quality.

In the handling procedures of fresh vegetables and fruits before packaging, chemical treatment with chlorinated water is commonly adopted; this is the only step by which the number of pathogens and spoilage microorganisms can be reduced (Brilhante, José, & Dantas Vanetti, 2012). However, chlorinated compounds can react with organic matter in fresh produce and form trihalomethanes and haloacetic acids, which are mutagenic and carcinogenic molecules. Therefore, various processing methods, including physical treatments such as gamma ray, electron beam, X-ray, and high hydrostatic pressure, as well as low-toxicity chemical and biological treatments have been investigated for their ability to reduce the bacterial counts in raw and minimally processed vegetables and fruits (Han, Gomes-Feitosa, Castell-Perez, Moreira, & Silva, 2004; Mahmoud, 2010; Maitland, Boyer, Eifert, & Williams, 2011; Niemira & Boyd, 2013). However, gamma ray, electron beam, and high hydrostatic pressure are not readily adopted in the agricultural industry owing to their high capital and operational costs. In addition, these treatments can cause adverse changes in texture or color in vegetable and fruit tissues (Han et al., 2004; Howard & Buescher, 1989). Therefore, an alternative treatment for microbial inactivation that does not affect the quality of cherry tomatoes is needed.

As an alternative treatment, ultraviolet-C (UV-C) irradiation has raised large attention (Manzocco, Da Pieve, & Maifreni, 2011; Mukhopadhyay, Ukuku, Fan, & Juneja, 2013). The germicidal effects of UV-C result from crosslinking between neighboring pyrimidine bases in DNA, which blocks microbial cell replication and eventually causes cell death (Allende & Artés, 2003; Yun, Yan, Fan, Gurtler, & Phillips, 2013). Many studies have focused on the use of UV-C irradiation as a non-thermal/non-aqueous intervention technology for eliminating natural microflora and foodborne pathogens from the contact surface of vegetables because of its numerous advantages over gamma or electron beams (Manzocco et al., 2011; Yun et al., 2013). In addition, in recent years, UV-C irradiation has been considered as an environmentally friendly technology to extend the shelf life of several vegetable and fruit products by reducing respiration rates and inhibiting the activity of cell wall-degrading enzymes (Bu, Yu, Aisikaer, & Ying, 2013; Bu et al., 2014; Jiang, Jahangir, Jiang, Lu, & Ying, 2010). For these reasons, UV-C has been widely applied in not only the pharmaceutical and cosmetics industries, but also in agriculture.

Modified atmosphere packaging (MAP) has been widely used in combination with refrigeration for vegetables and fruits packaged in polymeric films to maintain product safety and to extend the shelf life of these foods (Abadias, Alegre, Oliveira, Altisent, & Viñas, 2012; Singh, Giri, & Kotwaliwale, 2014). Active MAP is the practice of modifying the internal atmosphere composition of a package by displacing air with a gas mixture of desired composition (Das, Gurakan, & Bayindirli, 2006; Horev et al., 2012). Passive MAP is the generation of the modified gaseous environment by the natural process of produce respiration and the restricted gas exchange depending on the permeability of the packaging material after a transient period (Charles, Guillaume, & Gontard, 2008; Singh et al., 2014). Carbon dioxide (CO_2) is usually used to alter gas composition in MAP. The inhibition of microbial growth is mainly related to an enhanced CO_2 concentration, whereas the delay of quality change in fresh vegetables is a consequence of low oxygen (O_2) concentration (Horev et al., 2012).

Hurdle technology, a process that intentionally combines disinfection treatments, MAPs, and storage conditions, can be used to control microbial growth in vegetables and fruits, resulting in extension of the shelf life of a food product. Because every 10 °C rises in temperature generally increases biological reactions by two- or three-fold, hurdle technology has been successfully used for whole and minimally processed vegetables to improve microbiological safety and maintain the physiological quality of these products (Abadias et al., 2012; Sandhya, 2010).

A combined treatment of UV-C irradiation and MAP effectively inactivated the psychrotrophic and coliform bacteria in minimally processed lettuce without adversely affecting the sensory quality of the product (Allende & Artés, 2003), and a combined UV-C and O_2-enriched packaging method was more effective for controlling total aerobic mesophilic and psychrophilic bacterial growth on fresh-cut