

Critical Reviews in Food Science and Nutrition

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/bfsn20>

Maintaining antioxidant potential of fresh fruits and vegetables after harvest

Jose A. Villa-Rodriguez ^a, H. Palafox-Carlos ^a, Elhadi M. Yahia ^b & Gustavo A. Gonzalez-Aguilar ^a

^a Centro de Investigación en Alimentación y Desarrollo, A.C., Carretera a la Victoria km. 0.6, Apartado Postal 1735, Hermosillo, 83000, Sonora, México

^b Human Nutrition Program, Facultad de Ciencias Naturales, Universidad Autónoma de Querétaro, Avenida de las Ciencias S/N, 76230, Juriquilla, Querétaro, Qro, México

Accepted author version posted online: 25 Sep 2013.

To cite this article: Jose A. Villa-Rodriguez, H. Palafox-Carlos, Elhadi M. Yahia & Gustavo A. Gonzalez-Aguilar (2013): Maintaining antioxidant potential of fresh fruits and vegetables after harvest, Critical Reviews in Food Science and Nutrition, DOI: [10.1080/10408398.2012.685631](https://doi.org/10.1080/10408398.2012.685631)

To link to this article: <http://dx.doi.org/10.1080/10408398.2012.685631>

Disclaimer: This is a version of an unedited manuscript that has been accepted for publication. As a service to authors and researchers we are providing this version of the accepted manuscript (AM). Copyediting, typesetting, and review of the resulting proof will be undertaken on this manuscript before final publication of the Version of Record (VoR). During production and pre-press, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal relate to this version also.

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at <http://www.tandfonline.com/page/terms-and-conditions>

Maintaining antioxidant potential of fresh fruits and vegetables after harvest

Jose A. Villa-Rodriguez¹, H. Palafox-Carlos¹, Elhadi M. Yahia², Gustavo A. Gonzalez-Aguilar^{1*}

¹Centro de Investigación en Alimentación y Desarrollo, A.C., Carretera a la Victoria km. 0.6,

Apartado Postal 1735, Hermosillo 83000, Sonora, México

²Human Nutrition Program, Facultad de Ciencias Naturales, Universidad Autónoma de

Querétaro, Avenida de las Ciencias S/N, 76230, Juriquilla, Querétaro, Qro., México.

*Corresponding author: Gonzalez-Aguilar

Phone: 00-52-662-289-2400 ext 272

Fax:00 52 662 280 0422

e-mail: gustavo@ciad.mx

Abstract

The consumption of fruits and vegetables has increased in the past few years not only because of their attractive sensorial properties, but also for their nutritional and health benefits. Antioxidants are compounds found in fresh fruits and vegetables, and evidence for their role in the prevention of degenerative diseases is continuously emerging. However, antioxidants of some fruits and vegetables can be lost during handling after harvest, such as during minimal processing and storage. In this sense, postharvest treatments are needed to preserve the quality and antioxidant potential of fresh produce. Postharvest treatments and technological strategies (including ultraviolet light, controlled and modified atmospheres, heat treatments, and application of natural compounds such as edible coatings, active packaging, microencapsulation and nanoemulsion) show positive and promising results to maintain fruit and vegetable antioxidant potential. The purpose of this review is to analyze and propose the application of postharvest strategies to maintain or even improve antioxidant status of fruits and vegetables, offering options to maximize health benefits to consumers.

Keywords: Human health, Phytochemicals, Postharvest treatments, Technological strategies

Introduction

Numerous epidemiological studies have shown an inverse correlation between fruits and vegetables consumption and chronic diseases including different types of cancer and cardiovascular disease (Gonzalez-Aguilar, et al., 2010; Yahia, 2010). These studies have shown evidence that people who avoid fruit and vegetables completely, or who consume very little, are indeed at increased risk of these diseases. Therefore, the consumption of fruits and vegetables has increased around the world in the past few years not only because their attractive sensorial properties, but also for their nutritional and health benefits. In addition, the interest in understanding the type, amount, number, and mode of action of the different components of fruits and vegetables is becoming an important research topic in many laboratories.

Fruits and vegetables, apart from being good sources of vitamins, minerals, and fibers, are also rich sources of several other bioactive compounds with antioxidant properties (Yahia, 2010; Palafox-Carlos, et al., 2011). Examples of these compounds include carotenoids and other pigments, phenolic compounds, ascorbic acid, indoles, isothiocyanates and some vitamins, among others. The antioxidant content in fruits and vegetables has become an important quality parameter, in addition to external quality such as color, shape, size, etc.

Antioxidants from fruits and vegetables are very susceptible to degradation mainly due to some handling practices, fungal decay, chilling injury, irradiation, inadequate temperature and relative humidity, and several other types of stress (Chan & Tian, 2006; Yahia, 2010). These factors can reduce the antioxidant content and therefore the nutritional quality of fresh fruits and vegetables. Several postharvest treatments have been used to preserve the quality fruits and vegetables and they may also influence their antioxidant potential, including ultraviolet light,

controlled and modified atmospheres, edible coatings, heat treatments, and application of natural compounds, among others (Gonzalez-Aguilar, et al., 2010). In addition, technological strategies such as edible coating containing antioxidants, active packaging with antioxidant releasing systems, and microencapsulation and nanoemulsions of antioxidants on different matrices, represent interesting novel alternatives for delivering and incorporating important additional amounts of antioxidants and other nutritional compounds such as vitamins and antimicrobials into fruits and vegetables (Saenz, et al., 2009).

This article summarizes the recent findings concerning the effects of postharvest treatments on the antioxidant content of fruits and vegetables and proposes some strategies to maintain them.

Bioactive compounds: Their role in plant tissues and human health

Bioactive compounds are non-nutritional constituents that typically present in small quantities in foods. They are being intensively studied to evaluate their effects on health. These compounds vary widely in chemical structure and function being phytochemicals the most abundant group of bioactive compounds. There are differences in the literature regarding the definition of both concepts (Kris-Etherton, et al., 2002). Phytochemicals are plant secondary metabolites, which protect the plant against a variety of biotic and abiotic stresses such as those associated with changes in temperature, injury, pathogen attack, and UV irradiation. A common consequence of the exposure to many distinct types of stress conditions is the occurrence of oxidative stress, mediated by increased levels of reactive oxygen species (ROS) and free radicals. Many of these

compounds have shown antioxidant capacity (AOC) *in vitro* (mainly carotenoids, phenolic compounds and some vitamins), which has led to the use of the general term “antioxidants”.

Nowadays, it is well established that consumption of fruits and vegetables is associated with a reduced risk of developing chronic diseases (Holst & Williamson, 2008; Vicente, et al., 2009; Yahia, 2010). Most of the evidence suggests, apparently, that these protective effects are derived from antioxidant phytochemicals which can prevent or delay the oxidation of biomolecules. Nevertheless, today, the scientific community increasingly recognizes that their mechanism of action *in vivo* might be far more complex. Current evidence suggests that the cellular effects of dietary antioxidants may be mediated by their interactions with specific proteins central to intracellular signaling cascades (Holst & Williamson 2008). In addition, it has been observed that certain antioxidant phytochemicals metabolites are the bioactive form of these compounds (Larrosa, et al., 2010; Lotito, et al., 2011). Therefore, at the moment, the extent of the contribution of antioxidant phytochemicals to human health remains unclear. However, evidence of the benefit of consuming a diet rich in food containing antioxidant phytochemicals is very strong (Hertog, et al., 1992; Tulipani, et al., 2011; Visioli, et al., 2011). Hence, the best simple dietary public advice is still a generic “eat a large variety of plant-based foods.”

Considering the roles that antioxidant phytochemicals play in plant tissue and human health, an increasing interest with regard to the enhancement of these compounds is carried out with the objective to benefit both agricultural economy and public health. Several techniques have been proposed, including appropriate plant breeding, genetic modification, and postharvest treatments and strategies. The later represents a promising means to achieve this goal.

Postharvest treatments and their effects on fruit and vegetable antioxidants

Postharvest treatments have developed mainly to preserve freshness and to avoid microbial growth (Yahia et al., 2009), however, it has been shown that as a secondary response, some of these treatments affect the metabolic activity of the treated produce, such as triggering the biosynthesis of antioxidant compounds (Gonzalez-Aguilar, et al., 2010) (Fig. 1). In the next paragraphs we will discuss the effect of some postharvest treatments on the antioxidant content and stability of fresh fruits and vegetables.

Storage temperature

Both metabolic activity and deterioration process are accelerated during fruit ripening, and therefore cold storage is necessary to slow down these processes in order to maintain the postharvest quality. The postharvest quality of fruit and vegetables has been traditionally defined in terms of sensorial attributes (freshness, color, and absence of decay or physiological disorders), texture (firmness, juiciness, and crispness) and safety (deteriorative and pathogenic microorganism). Hence, most of the research done in this field has focused on the effect of storage temperature on the sensorial and safety qualities rather than on the nutritional quality. However, in view of the growing knowledge about the importance of the consumption of fruits and vegetables for health, research on the effects of storage conditions on antioxidants has been gaining importance in the last decade.

Storage temperature, in addition to light and oxygen exposure, is one of the key factors influencing stability of antioxidants in fruits and vegetables after harvest. As far as fruits and vegetables are concerned, evaluating the effect of storage conditions on the content of

antioxidants is not an easy task since it can be influenced by a numerous of factors such as product species (Kevers, et al., 2007; Piljac-Zegarac & Samec, 2010), genotype (Cordenunsi, et al., 2005; Díaz-Mula, et al., 2009), degree of fruit maturity (Shin, et al., 2008; Kruger, et al., 2011), sensitivity to chilling temperature (Gonzalez-Aguilar, et al., 2004; Wang, et al., 2008), temperature (Ayala-Zavala, et al., 2004; Javanmardi & Kubota, 2006), relative humidity (Shin, et al., 2007; 2008), and storage duration (Shin, et al., 2007; 2008; Biglari, et al., 2009).

Several studies have shown significant fluctuations in the content of antioxidants in fruits and vegetables at low and at room temperatures. Piljac-Žegarac and Dunja Šamec, (2010) found that total phenols (TP) and total flavonoids (TF) were significantly higher in cherry, strawberry and raspberry fruits stored at 25 °C compared to their levels in these fruits stored at 4 °C. Ayala-Zavala et al. (2004) observed that TP and total anthocyanins (TA) increased continuously in strawberry fruit stored at 10 and 5 °C. However, the TP of strawberry fruit stored at 0 °C were maintained for over 13-days storage period. This trend was observed in other fruits and vegetables such as nectarine, banana, kiwi, apple, lettuce, pepper, tomato, and spinach (Kevers, et al., 2007). In contrast, Mirdehghan et al. (2007) and Leja et al. (2003) found an increase in TP content in pomegranate arils and apple fruit, respectively. The authors argued that this increase was probably due to stimulation of the activity of some enzymes involved in phenolic biosynthesis in cold storage (Hamauzu, 2006). Little is known about the effects of storage temperature on lipophilic antioxidants such as carotenoids, tocopherols, sterols, and some unsaturated fatty acids (Villa-Rodriguez, et al., 2011). β -carotene content of tomatoes, for instance, was observed to increase during storage when fruit were still in the ripening process, and this increase was more pronounced at higher temperatures of up to 25 °C; whereas, in some

sweet potato cultivars, no increase in β -carotene during storage occurred as the synthesis of carotenoids was already completed by the time of harvest (Watada, 1987). However, temperatures above 30 °C can suppress carotenoid biosynthesis (Wills, 1998). This behavior has been found in β -carotene content in different varieties of mango stored at 5 °C for 12 days (Gonzalez-Aguilar, et al., 2008). The study of the influence of storage temperature on the content of tocopherols, sterols and unsaturated fatty acids has not been addressed yet and is imperative because of their nutritional and health importance.

The findings mentioned above suggest that the reactions taking place within the fruit at higher temperature may facilitate the formation of compounds with enhanced AOC, even at the point (in some cases) when fruit attributes (taste, smell, appearance and texture) have already significantly deteriorated. However, although the biosynthesis of antioxidant compounds is increased at higher temperatures, the AOC is superior in those stored at low temperature. This could be happening due to a high production of ROS from those fruits and vegetables stored under higher temperatures, since their respiration rate and metabolic activity is enhanced (Piljac-Zegarac & Samec, 2010). However, it is necessary to pay special attention to those commodities sensitive to chilling injury as sensory, safety and nutritional quality is diminished by low temperatures limiting its marketing (Maul, et al., 2011). Some insights to chilling injury tolerance comes from studies in which increased activity of antioxidant enzymes and antioxidant compounds (mainly phenolics) have been observed (Shin, et al., 2007).

The use of temperature control for extending the shelf-life of fresh fruits and vegetables after harvest is widely recognized and used; however, more research is still needed on the effects of this technology to maintain the nutritional quality, especially their antioxidant content. In

addition, even though the overall quality is better maintained at lower temperatures ($<10^{\circ}\text{C}$, for those not sensitive for chilling injury), temperatures above 10°C significantly increased the nutritional quality of these commodities. More extensive and deep research in this field is necessary before proper recommendations on the effects of optimal storage temperature of fruits and vegetables storage on nutritional quality are made. Further studies should address the biosynthesis of antioxidant compounds and analyze the expression of genes involved, in order to have conclusive evidence. In addition, since the produce maintains a better sensory and safety quality under low temperatures ($<10^{\circ}\text{C}$), the combination of this treatment with other postharvest technologies (e.g. UV irradiation) which have shown to increase the content of antioxidant compounds should be tested.

Irradiation

Plant cells have developed highly sophisticated light-sensing mechanisms that are intricately associated with fundamental processes (e.g. photosynthesis) and multiple photoreceptors that are also able to perceive light and activate its response processes. Among these photoreceptors are the red (R)/far-red (FR) light-sensing phytochromes and the blue (B) light-sensing cryptochromes and phototropins (for an extensive review see Azari, et al. 2010). Phytochromes are not photoprotection mechanisms but molecules involved in perception of light. Studies elucidated that many antioxidant compounds were involved in these processes to scavenge the excess energy or ROS in the photosynthetic apparatus and their content are increased under stressful conditions (Niyogi, 1999). With this knowledge and with the recognition of health benefits of antioxidants, the manipulation of light signaling machinery could be useful.

Food irradiation is a well established physical method that has proved its efficacy in the preservation of quality of some horticultural commodities when applied at adequate doses causing minimal modification in the flavor, color, taste, and other quality attributes (Gonzalez-Aguilar, et al., 2010). Irradiation treatments of fruits and vegetables involve ionizing or non-ionizing radiation, however the research of this technology has focused mainly on sensorial and safety quality issues (Thomas & Sparks, 1984; Thomas & Bramlage, 1986; Thomas & Moy, 1986; Thomas & Diehl, 1988). Ionizing radiation is a powerful electromagnetic radiation that could be applied by electron beam, X-rays (machine generated), or gamma rays (from ^{60}Co or ^{137}Cs sources) (Reyes & Cisneros-Zevallos, 2007; Jimenez, et al., 2011;), while the non-ionizing radiation is comprised by electromagnetic radiation that does not carry enough energy/quanta to ionize atoms and molecules, represented by ultraviolet rays (UV-A, UV-B, & UV-C), visible light, microwaves, and infrared radiation (Alothman, et al., 2009a; Rawson, et al., 2011). Although, irradiation could break chemical bonds, remove electrons (forming ions, free radicals, or ROS), and induce water radiolysis, it has been reported that the stress caused by these preservation techniques can affect the antioxidant status through the induction of ROS in living tissue. Therefore, a growing scientific interest has emerged in order to better understand the effects of radiation on the antioxidant status of fruits and vegetables and on the compounds responsible for such activity.

Over the last few years, a number of studies have suggested that the effects of irradiation on the antioxidant status of fruits and vegetables is a function of the radiation source, dose, time of exposure, storage conditions, treated produce and antioxidant sensitivity (Alothman, et al., 2009a; Gonzalez-Aguilar, et al., 2010; Jimenez, et al., 2011). Tables 1 and 2 show some of the

current studies on the effects of ionizing and non-ionizing radiation on the antioxidant content in fruits and vegetables, respectively.

Electron beam and γ -irradiation are the most used ionizing radiation to try to increase the antioxidant content in the produce (Table 1). The application of electron beam irradiation has resulted in a negligible effect on antioxidants such as phenolics, carotenoids and ascorbic acid, but a slight antioxidant loss has been observed compared to the untreated produce (Reyes & Cisneros-Zevallos, 2007; Girennavar, et al., 2008). On the other hand, γ -radiation has showed a positive effect on the antioxidant content, increasing the content of phenolics (Table 1), but there has been a negative effect on the content of ascorbic acid. Jimenez et al. (2011) evaluated the effect of γ -irradiation on green onion DNA integrity, TP, ascorbic acid and AOC. The authors found a slight increase in TP concentrations and that γ -radiation does not lead to an apparent DNA change, but there was a decrease in the ascorbic acid content. These results mentioned above suggest, apparently, that ionizing radiation involves an oxidative damage process that further results in the loss of antioxidants by a direct and indirect way. In the first case, radiation acts directly on the matter, causing the breakdown of molecules such as enzymes related with the synthesis of phenolics, carotenoids and ascorbic acid. In the second case, irradiation acts through water radiolysis and, therefore, the different water radiolysis products reacts with other compounds causing significant chemical changes, like hydroperoxide and ROS formation. Therefore different antioxidant compounds have a fundamental role in the plant antioxidant response toward ionizing radiation exposure.

In fact, current studies performed on the effects of non-ionizing radiation on the antioxidant content in fruits and vegetables have reported an increase in TP, TA and AOC (Table

2) attributed to its effect on phenylpropanoid metabolism enzymes activation. However, other reports have postulated that this increase could be due to the degradation of polymerized structures by irradiation resulting in a higher extractability (Variyar, et al., 2004). In addition, little is known on the changes of other antioxidants such as carotenoids, tocopherols, and ascorbic acid.

Recently, Liu et al. (2011) reported the effect of UV-B irradiation on the content of lycopene in tomato exposed to different doses (10, 20, 40 and 80 kJ/m²). They found that the highest dose of 80 kJ/m² resulted in an increment of lycopene content, but showed negative effects on texture, colour, and other type of antioxidants. With regards to ascorbic acid, a few studies have shown that non-ionizing irradiation treatments affect negatively their content in fruits (González-Aguilar, et al., 2007; Alothman, et al., 2009b; Hussain, et al., 2010). The later authors found that irradiation treatment reduce ascorbic acid content of fresh-cut mangos, phenols and flavonoids content increased contributing in higher extent to the AOC compared with no-treated fruit.

The use of some types of irradiation has proved to be beneficial to improve the sensorial, safety and nutritional quality of some horticultural commodities (Gonzalez-Aguilar, et al., 2010). This technology can be used for the food industry to obtain fresh-produce with higher antioxidant content that could be used for the formulation of nutraceuticals products in a cost-effective manner since the process is inexpensive and easy to adapt. The Spanish pharmaceutical “Actafarma” recently acquired licensing rights from CEBAS-CSIC (Spain) using this method to produce enriched resveratrol-grapes and nutraceutical “*Revirox*” which is currently being

marketed. This is a clear example of the scalability of UV treatment which could be adapted to other produce.

Irradiation promises to be an excellent technology to increase the content of antioxidants in fruits and vegetables. However, in view of the inconsistencies of the effects of irradiation treatment on the antioxidant content and type in plant produce, studies should be carried out under controlled conditions such as sources of irradiation, radiations doses, storage conditions and type of antioxidants to obtain comparable results and better knowledge. There is a lack of studies considering biochemical and molecular mechanisms by which UV irradiation increase or decrease the antioxidant status of fruits and vegetables. In this sense, more research is need it regarding to the mechanism by which UV triggers the increase of antioxidants since no receptors for some kinds of radiation has been identified so far (e.g γ and UV-C irradiation). In addition, further studies are needed on the effect of this technology on the content of lipophilic antioxidants, which forms an important part of the antioxidant system and nutritional value of the produce.

Controlled and modified atmospheres

Controlled atmosphere (CA) and modified atmosphere (MA) refer to the deliberate or undeliberate manipulation of the composition of the gaseous environment during the preservation (storage, packaging or transport) of produce. The control of gas constituents of CA is more precise and stable while with MA air composition changes continuously. CA and MA may be achieved in large facilities such as storage rooms and transport vessels or in individually wrapped containers or packages using specialized packaging systems.

This is a fast-growing area of postharvest technology that is 'ripe' for innovation (Beckles, 2012). The use of CA and or MA to prolong the storage and shelf life of horticultural commodities by decreasing metabolism and suppressing postharvest decay has been well established and widely used to store, transport and pack various fruits and vegetables (Yahia, 2009).

The effects of CA and MA on antioxidant content depend on several factors such as type of produce and cultivar, concentrations of O₂, CO₂ and other gases in the atmosphere, temperature and duration of storage, and the antioxidant evaluated. In terms of concentration of gases, an atmosphere with high O₂ pressure elicit a favorable response in the content of phenolic compounds (Singh & Pal, 2008; Yang, et al., 2008; Odriozola-Serrano, et al., 2009; Duan, et al., 2010; Simões, et al., 2011;), while low O₂ maintains the levels of ascorbic acid and carotenes (Singh & Pal, 2008; Simões, et al., 2011). For example, Ayala-Zavala et al. (2007) and Yang et al. (2008) showed an increase in TP, TA and total AOC with an increase in O₂ concentrations (80-100 kPa) in strawberry and Chinese bayberry fruit respectively. Similarly, Duan et al. (2011) showed that a treatment with pure oxygen markedly increased AOC, TA and TP of litchi fruit. They observed no significant difference in the contents of TP and TA between control and pure oxygen-exposed fruit for 2 days. After 4 and 6 days of storage, the contents of total phenolic compounds and anthocyanins in pure oxygen-exposed fruits were much higher than that of controls. Despite that literature shows positive results, it is necessary to evaluate the advantages/disadvantages of practical application of pure O₂ treatment. With this in mind, we considerer that it would be feasible the application of 100% O₂ atmosphere due to the relative simple way to adapt the system into any refrigerated chamber and the possibility of recirculation

the O₂. However, the analysis of balance cost-benefit it would be taken in consideration by the producer due the high cost that O₂ may exhibit and according to the type of produce.

The effects of CA containing 2.5, 5, 8, and 10 kPa O₂ with 2.5, 5, and 10 kPa CO₂ has been studied in guava fruit (Singh & Pal, 2008). They observed that fruits stored at 2.5–5 kPa O₂ had higher ascorbic acid content at the ripe stage than those stored in atmospheres with 8 or 10 kPa O₂. The same behavior was observed in ascorbic acid content and total carotenoids in fresh-cut pineapple (Montero-Calderon, et al., 2010) and baby carrots (Simões, et al., 2011) under low O₂ atmosphere (12% O₂, 1% CO₂ and 2 kPa O₂ 15 kPa CO₂, respectively). These protective effects could be due to the low interaction between these compounds and O₂ avoiding their oxidation (Singh & Pal, 2008; Simões, et al., 2011). Common recommendation to ensure the sensorial and safety quality as well as to prolong the storage-life of fruits and vegetables is to reduce the levels of O₂ and increase CO₂. Nevertheless, according to the literature mentioned above and our experience, these conditions have not shown to increase the content of antioxidants. So, can we manipulate the levels of antioxidants by modifying the atmosphere surrounding the commodity without affecting the sensorial and safety quality? Based on literature evidence, it appears that there is no simple answer to this question. For example, It has been shown that exposure of harvested horticultural crops to superatmospheric O₂ (60-100%) levels may stimulate, have no effect, or reduce the rate of respiration, depending on the commodity, maturity stage, time, and temperature of storage (Kader & Ben-Yehoshua, 2000). Therefore, the detailed examination of such treatments and their impact on fruit and vegetable quality is nevertheless highly essential, because different plant tissues behave in a variable manner upon exposure to different CA and MA conditions. CA and MA technology is a

promising means of modifying the contents of antioxidants because of its efficacy to prolong the shelf-life of fruits and vegetables. Further research is needed to address i) the biochemical (such as enzymes that regulate the synthesis and breakdown of antioxidants) and molecular (transcripts levels of this enzymes), and ii) the detailed examination in the profile of various antioxidant classes (ascorbic acid is highly altered by modifying the gas composition). With this in mind, we could elucidate the right concentrations of gases that improve the antioxidant content in fresh-produce without affecting sensorial and nutritional quality.

Natural volatile compounds

Several natural volatile compounds such as allyl isothiocyanate (Chanjirakul, et al., 2007; Wang & Chen, 2010; Wang, et al., 2010), ethanol (Chanjirakul, et al., 2006; Ayala-Zavala, et al., 2008b), essential oils (Chanjirakul, et al., 2007; Ayala-Zavala, et al., 2008b; Serrano, et al., 2008) and methyl jasmonate (MJ) (Gonzalez-Aguilar, et al., 2006; de la Peña-Moreno, et al., 2010a; 2010b) have been used to maintain and enhance the quality and antioxidant content in fruits and vegetables. Nevertheless, among these treatments, MJ has proved to be the most effective.

The jasmonate family which consists of cis-jasmone, jasmonic acid, and MJ, are fatty acid-derived cyclo pentanones that occur ubiquitously in the plant kingdom (Cohen & Flescher, 2009). Today, it is well recognized that MJ plays important roles in plant growth and development, fruit ripening, and responses to environmental stress (Wang, et al., 2009). When is exogenously applied as a postharvest treatment it can induce the synthesis of antioxidants (Gonzalez-Aguilar, et al., 2010).

The earliest event in plant cells exposed to MJ is their recognition mediated by plasma membrane-localized receptors. Elicitor perception activates receptor-coupled effectors such as GTP-binding proteins or protein kinases and phosphatases which further mobilize or generate diverse signaling molecules directly or indirectly such as free calcium, NO₂ and ROS (Faurie, et al., 2009; Gonzalez-Aguilar, et al., 2010). These inducible mechanisms are intimately involved in H₂O₂ metabolism and phenylpropanoid pathway.

Recently, de la Peña-Moreno et al. (2010a; 2010b) showed that exogenous application of MJ induced an enhancement in the levels of phenolic compounds such as myricetin, quercetin and, particularly, kaempferol in raspberries and strawberry. Wang et al. (2009) observed that Chinese bayberries treated with 10 µmol L⁻¹ of MJ exhibited higher levels of TP, TF, and TA, as well as individual phenolic compounds such as gallic and protocateic acids, myricetin, quercetin-3-O-rutinoside, and cyanidin-3-glucoside contents during storage at 0 °C for 12 days, compared to the controls. Similarly, enhanced flavonoid content and antioxidant activity was observed in blackberry (Wang, et al., 2008), anthocyanin accumulation in apple (Rudell & Mattheis, 2008), and resveratrol biosynthesis in grapes (Vezzulli, et al., 2007). On the other hand, it has been observed that MJ maintains the levels of other antioxidants such as carotenoids and ascorbic acid rather than enhancing their contents in fruits and vegetables (Kim, et al., 2007; Ayala-Zavala, et al., 2008b). Moreover, disease resistant (González-Aguilar, et al., 2004; Meng, et al., 2009; Cao, et al., 2010) and decrease of chilling injury (Gonzalez-Aguilar, et al., 2004; Cao, et al., 2010; Zhang, et al., 2012) have been observed suggesting that the use of MJ has a potential application in postharvest treatments, especially for tropical and subtropical origin.

Despite the fact that there is conclusive evidence about the effectiveness of MJ, the exact mode of action to reduce chilling injury, protect against deteriorative microorganism and increase the antioxidant levels remains unclear. Growing evidences suggest that these events are linked. For example, it has recently been shown that increased levels of arginine-related metabolites (free polyamines or proline) and abscisic acid occur in response to MJ (Zhang, et al., 2012). In addition, it has been proposed that MJ interacts with various stress responsive signal networks, mainly salicylic and abscisic acid (Wang & Buta, 1994; Gonzalez-Aguilar, et al., 2004; Manjunatha, et al., 2010). These interactions throughout the activation of specific genes either directly or indirectly have been related with the activation of defense mechanism of plant tissues. Nevertheless, while these studies have provided some information on the involvement of various signal molecules, further elucidation is required at the molecular level for obtaining a comprehensive picture.

In summary, the use of postharvest treatments to improve the antioxidant content and therefore the nutritional quality of fruits and vegetables seems to be a good alternative since it can be performed in a relatively simple and cost-effective manner. Nevertheless, enhanced concentration of antioxidants is not an easy task, which in turn, makes it difficult to define precise targets in terms of the type of antioxidants and their concentration. At least two critical lines of research need to be pursued to gain a better understanding of the effects of postharvest treatments on nutritional quality of fruits and vegetables:

- i) It is important to investigate the factors that modulate stress response as well as the possible interaction between the different stresses and the response of the tissue. The applicability of “omics” technologies such as transcriptomics, proteomics and

metabolomics, as additional tools will be crucial to obtain a global picture of these effects. Transcriptomics (microarray-based gene expression analysis) and proteomics (two-dimensional electrophoresis-based proteome) analysis have the potential to screen many metabolic pathways simultaneously for alterations in gene expression and protein levels. While Metabolomics provides a global description of all the metabolites present in the produce and a better understanding.

- ii) It is recommended to investigate the interaction and combination of postharvest treatments with new technological strategies to ensure and promote the antioxidant potential in fresh fruits and vegetables. Improved understanding of these interactions may yield benefits both for the public health and the agricultural economy.

A major challenge for researchers in the future will consist of working out the best combinations of beneficial components of fruits and vegetables according to existing genetic profiles while minimizing antagonistic interactions and determining the duration of exposure and timing.

Strategies to increase antioxidant potential in fruits and vegetables

The new generation of food processes, packages, coatings or food matrices is being especially designed to increase their functionalities by incorporating natural bioactive compounds, such as antioxidants, antimicrobials, probiotics and flavors. These approaches can be useful to extend shelf-life and reduce the risk of pathogen growth on food surfaces as well as to provide a product with health benefits to the consumer. Besides, health benefits could be provided to consumer if

the antioxidant potential/content in fresh products is improved or maintained. Several studies and strategies are being developed with excellent potential to accomplish this purpose, which includes basically the incorporation of bioactive compounds directly to the edible coatings, incorporation into the package or microencapsulation.

Edible coatings

An edible coating is defined as a thin layer of material which can be consumed, and provides a barrier to moisture, gases and solute movement for the food (Bourtoom, 2008). Edible films and coatings are applied on many products to control moisture transfer, gas exchange or oxidation processes. One major advantage of using edible films and coatings is that several active ingredients can be incorporated into the polymer matrix and may even be consumed with the food, thus enhancing safety or even nutritional and sensory attributes (Martín-Belloso, et al., 2009; Rojas-Grau, et al., 2009). Nowadays, the new generation of edible coatings is being especially directed to increase the nutritional and health potential of fruits and vegetables by incorporating natural bioactive compounds, such as antimicrobials, probiotics, flavors, and moreover, antioxidants (Fig. 2).

Generally, edible coatings are classified into three categories taking into account the nature of their components. Polysaccharides (such as cellulose derivatives, starch, alginate and chitosan) are abundant, inexpensive, and easy to handle. However, these compounds are generally very hydrophilic resulting in poor water vapor and gas barrier properties (Bourtoom, 2008). Proteins (such as zein, soy, collagen, whey proteins and gelatin), generally possess good mechanical and optical properties and they are good barriers against the transport of O₂ and CO₂, however, their

use involves poor water vapor barrier property (Han, et al., 2004; Mirdehghan, et al., 2007). Finally, lipids (such as glycerol esters, paraffin wax and beeswax) block transport of moisture due to their relative low polarity. Their waxy taste and texture, greasy surface and potential rancidity, depending on their composition, changes the functionality of these materials, as each component offers different properties to the composite matrix (Janjarasskul & Krochta, 2010).

Recent studies have been performed in order to demonstrate the efficacy of edible coating on improving the antioxidant potential of fruits and vegetables, in which the polysaccharide-based coating as chitosan has been the principal material. Edible coatings are also an excellent vehicle to enhance the nutritional value of fruits and vegetables by carrying basic nutrients that are lacking or present in low amounts in fruits and vegetables (Lin & Zhao, 2007). Despite the growing interest in incorporating antioxidants compounds into fresh produce, few studies have been reported (mentioned in the following paragraphs) suggesting that the application of edible coatings or integration of bioactive ingredients into edible films or coatings improve their functional and antioxidant properties.

Chitosan-based edible coatings were used to extend the shelf-life and enhance the nutritional value of strawberries (*Fragaria × ananassa*) and red raspberries (*Rubus ideaus*) (Ribeiro, et al., 2007). Three chitosan-based coatings (chitosan, chitosan containing 5% Gluconal[®] CAL, and chitosan containing 0.2% DL- α -tocopheryl acetate) were studied. Results indicated that chitosan-based coatings containing calcium or tocopherol significantly increased the content of these nutrients in both fresh and frozen fruits. One hundred grams of coated fruits contained about 34–59 mg of calcium, or 1.7–7.7 mg of α -tocopheryl acetate, depending on the type of fruit and the time of α -tocopherol storage, while uncoated fruits contained only 19–21 mg

of calcium or 0.25–1.15 mg of (Han, et al., 2004). Also, the efficacy of polysaccharide-based (starch, carrageenan and chitosan) coatings to extend the shelf-life of strawberry fruit (*Fragaria ananassa*) was also demonstrated, mainly for industrial applications (Ribeiro, et al., 2007).

On the other hand, the combined application of an edible coating containing chitosan was studied on carrot sticks (Simões, et al., 2009). The use of the edible coating containing chitosan preserved the overall visual quality and reduced surface whiteness during storage, and moreover, the content of total phenolics markedly increased in coated carrot sticks stored under moderate O₂ and CO₂ levels. The authors concluded that the combined application of edible coating containing chitosan and moderate O₂ and CO₂ levels maintained quality and enhanced phenolic content in carrot sticks. Also in carrots, Mei et al. (2002) reported that Xanthan gum coating 5% Gluconal Cal, a mixture of calcium lactate and gluconate, and 0.2% α -tocopherol acetate (vitamin E) improved the desirable surface color of carrots and β -carotene content without affecting the taste, texture, and fresh aroma and flavor.

In the case of fruits, Tapia et al. (2005) studied the use of edible coatings mixed with antioxidants to reduce the deleterious effects imposed on fresh-cut fruits such as apples and papaya by minimal processing. These edible films helped to extend their refrigerated shelf life by reducing moisture loss and gas exchange. The antioxidants used were citric acid and ascorbic acid; cysteine and glutathione. In pears, the effect of alginate-based (2%, w/v), pectin-based (2%, w/v) and gellan-based (0.5%, w/v) edible coatings containing *N*-acetylcysteine at 0.75% (w/v) and glutathione at 0.75% (w/v) on the quality and antioxidant content in fresh-cut ‘Flor de Invierno’ pears was investigated (Oms-Oliu, et al., 2008). The incorporation of *N*-acetylcysteine and glutathione into edible coating formulations not only improved the quality characteristics,

but also the ascorbic acid and total phenolic content. Besides, in pear wedges coated with alginate, gellan and pectin including antioxidants contributed to maintaining their antioxidant potential.

Tapia et al. (2008) formulated alginate and gellan-based edible coatings containing ascorbic acid for fresh-cut papaya pieces. They observed that alginate coatings appeared to perform better on ascorbic acid retention, probably because of slightly better gas barrier properties. Authors also reported that the incorporation of ascorbic acid to the coatings resulted in a substantial increase in the ascorbic acid content of the fresh-cut product, thus helping to preserve the naturally occurring amounts of this compound throughout storage. Similar results were observed by Ayrançi & Tunc (2004) who reported that antioxidants such as citric or ascorbic acid, incorporated as an additive into a methylcellulose coating, extensively reduced ascorbic acid losses in whole apricot and peppers.

In squash, Ponce et al. (2008) observed an improvement of the antioxidant protection of the minimally processed squash using chitosan films enriched with essential oils in *in vitro* and *in vivo* studies. Chitosan films enriched with rosemary and olive improved the antioxidant protection of the minimally processed squash offering a great advantage in the prevention of browning reactions which typically result in quality loss in fruits and vegetables.

According to these reports, important progresses have been achieved regarding the application of edible coating to improve the antioxidant potential of fruits. Besides, two general strategies could be distinguished in general in these studies: 1) incorporation of antioxidants into the edible coating or 2) application of the edible coating by itself to stimulate the synthesis of antioxidants in the fruit. No matter which strategy is used, both are effective to ensure a rich

source of antioxidant. Also, it is important to point out that the concentration of nutrients added to the coatings must be carefully studied to know the effects on their basic functionality, namely on their barrier and mechanical properties.

A relevant limitation that edible coating may present is that many compounds used in the development of edible films and coatings, including edible matrixes and other ingredients, can affect the taste and odor of coated products (Rojas-Graue, et al., 2009). These compounds have their own characteristic flavor, and interaction between ingredients may generate some changes in the sensory profile. For instance, the use of chitosan-based coatings may generate slight flavor modifications because of its typical astringent / bitter taste. Vargas et al. (2006) observed that chitosan led to a significant decrease in the aroma and flavour of strawberries, especially when high concentrations of oleic acid were used with the purpose of increasing the moisture barrier properties. Han et al. (2005) and Chien et al. (2007) reported that the application of a chitosan-based coating resulted in no perception of astringency in fresh strawberries and pitahayas, respectively. Despite of these limitations, the application of edible coatings to deliver active substances is one of the major advances reached so far to increase the shelf-life and antioxidant content of fresh-cut produce.

Micro and nanoencapsulation

Interest in the consumption of fresh fruits is, to a large extent, due to their content of bioactive nutrients and their importance as source of dietary antioxidants. There is a growing demand for delivery of antioxidants through functional foods with the related challenge of protecting their bioactivity during food processing and subsequent passage through the gastrointestinal tract (Bakowska-Barczak & Kolodziejczyk, 2010). There is growing interest in enhancing the health

benefits of food products through microstructural design and/or the incorporation of bioactive molecules associated with chronic disease prevention into complex food matrices (Nik, et al., 2011)

As mentioned above, antioxidants could be incorporated into the package, coating or even directly on the fruits and vegetables products. However, antioxidants are subject to process and storage degradation. Thus, several solutions are being developed to protect the antioxidant stability and ensure fruits and vegetables antioxidant potential. Recently, emulsions, micro and nanoencapsulation in different matrices have shown important progresses in this field, moreover with lipids (Almeida, et al., 2009). Because of their unique properties, lipid-based micro and nanoencapsulation systems enhance the performance of antioxidants by improving their solubility and bioavailability, *in vitro* and *in vivo*, and preventing their unwanted interactions with other environmental and food components (Mozafari, et al., 2006). Also, a variety of food-grade proteins and polysaccharides can also be used to manufacture biopolymer particles, including whey proteins, casein, soy proteins, gelatin, zein, starch, cellulose, and various other hydrocolloids (Matalanis, et al., 2011).

The selection of particular lipid, proteins, polysaccharides and other components to form biopolymer particles depends on a number of factors: (i) the ability of the components to be assembled into particles; (ii) the functional requirement for the particles (e.g., size, charge and stability to environmental conditions); (iii) legal status, cost, ease of use, and consistency of the ingredients and processing operations. Micro and nanoencapsulation is defined as a technology to pack substances in miniature, focusing mainly on nano-sizes, making use of techniques such as nanocomposite, nanoemulsification, and nanostructuring. Nanoemulsions are a class of

extremely small droplets that appear to be transparent or translucent with a bluish coloration. They are usually in the range 50 to 200 nm but much smaller than the range (from 1 to 100 μm) for conventional emulsions. This encapsulation technology may provide final fruit and vegetables product functionality (including controlled release of the core) which is expected to be maintained during storage (Fig. 4). Within the food engineering field, protection of bioactive compounds such as vitamins, antioxidants, proteins, and lipids as well as carbohydrates may be achieved using this technique for the production of functional foods with enhanced functionality and stability (Quintanilla-Carvajal, et al., 2010). Moreover, encapsulation of antioxidants may prevent them from being degraded during digestion in the stomach, thereby enhancing subsequent bioactivity and bioavailability (Takahashi, et al., 2009). However, more research efforts are still needed for the understanding of the potential impacts of nanoencapsulated antioxidants on the human body and environment to address the public concerns.

A very useful method to enhance the stability of antioxidants is the micro and nanoencapsulation by the spray drying technique, which provides powders with low humidity and good quality that are easy to store and apply. Microencapsulation by spray drying is the most economical and flexible way that food industry can encapsulate antioxidants. Thus, this technology is now becoming available to satisfy the increasingly specialized needs of the market. In addition, fluid-bed process is also becoming a promising encapsulation technique for large-scale production of flavor powders to be applied in food industry (Madene, et al., 2006). Lycopene microcapsules were prepared by a spray-drying method using a wall system consisting of gelatin and sucrose with positive results. This study would be helpful for the industrial

application of lycopene and offer interesting expectations for encapsulation for other antioxidants (Shu, et al., 2006).

Microencapsulation of bioactive compounds from fruits have been demonstrated and implemented with promising result, but further work is still needed on this topic. To prevent grape seed oil oxidation, and to increase the utility of grape seed oil, it was microencapsulated with soybean protein isolate and malt dextrin (Xiaomei & Yuefeng, 2009). The authors reported that the preservation periods of the microencapsulated grape seed oil is about 363 days, clearly longer than that of the grape seed oil without any treatment (Xiaomei & Yuefeng, 2009). Also in grapes, anthocyanins from Cabernet Sauvignon (*Vitis vinifera* L.) grapes were encapsulated with different carrier agents. Maltodextrin, maltodextrin/ γ -cyclodextrin and maltodextrin/arabic gum tested as carrier agents and the combination of maltodextrin/arabic gum presented the longest half-life time and lowest degradation constant for all the conditions evaluated (Burin, et al., 2011). Bakowska-Barczak and Kolodziejczyk, (2010) studied the concentration of bioactive compounds in black currant berries (*Ribes nigrum* L.) and retention of black currant polyphenol compounds and their antioxidant activity after microencapsulation by spray-drying. Radical scavenging activity studies demonstrated significant antioxidant activity of microencapsulated powders before and after storage.

On the other hand, encapsulation of individual antioxidants has been achieved by Cai-yuan et al. (2004), which reported that soybean protein in combination with ethylcellulose and emulsifier was used as wall material for microencapsulating quercetin. The antioxidation of quercetin microcapsule was better than the control artificial antioxidant containing the same concentration in oils and was enhanced with the increasing amount of quercetin microcapsule.

Similarly, Almeida et al. (2010) studied the improvement of the rutin photostability and its prolonged *in vitro* antioxidant activity of its association with nanostructured aqueous dispersions. Authors concluded that rutin-loaded nanostructures represent alternatives to the development of innovative carriers of antioxidants for application in food products or medicines.

At present, our understanding of how to create biopolymer particles with specific functional attributes is limited, and a better understanding of structure-function relationships is needed. Identification of the most appropriate ingredients and conditions required to create these particles requires knowledge of the molecular and functional characteristics of the biopolymers used, as well as of the physicochemical mechanisms underlying particle formation (Matalanis, et al., 2011). For practical purpose, the application of encapsulation delivery systems on an industrial scale is limited to those systems that can be manufactured economically and that are robust enough for commercial applications.

In this context, incorporation of antioxidants or radical scavengers into encapsulation or emulsion particles (Fig. 5) could be a suitable delivery system in order to transport them as active ingredients or additives that may improve or ensure the antioxidant and nutritional state of fresh fruits and vegetables. As we have observed in the literature, the emulsification and encapsulation technologies are being well understood, there is a clear development in this field in the last decade, and new studies are continually emerging. However, it is necessary to explore new practical applications. We visualize that encapsulation using different matrices is an attractive and efficient strategy to carry and deliver antioxidants into fresh produces packages, or the application of encapsulated antioxidants directly on fruits to ensure and promote their antioxidant status, which would benefit not only the produce but also promote health benefits to

consumers. Studies on these matters are of great importance nowadays and extensive research is required in order to take advantage of this technology.

Active packaging

Active packaging is defined as a system in which the package interacts with the product or the headspace, in order to maintain the nutritional and sensory quality, fresh-like appearance, and safety of the food product (Appendini & Hotchkiss, 2002; Ozdemir & Floros, 2004; Lu, et al., 2009). This new emerging technology has interesting perspectives for practical application in postharvest management. Examples of active packaging include the use of moisture scavengers, flavor emitters/adsorbents, and antioxidants.

Active packaging technology has been applied for antimicrobial purposes mostly in fruits, and using mainly essential oils or polyphenols as antimicrobial agents or additives (Ayala-Zavala & Gonzalez-Aguilar, 2009, 2010; Ayala-Zavala, et al., 2009; Wang, et al., 2011) basically in order to ensure product safety and quality. However, the same mechanisms or principles may be applied to increase the antioxidant potential in fruits and vegetables contained in the package (Fig. 3). According to Ayala-Zavala et al. (2008c) antioxidant active packaging systems can be divided into four groups according to the mechanism of action of the antioxidant compound: (i) the antioxidant is released to the headspace of the package in order to interact with the product surface; (ii) the antioxidant compound is included into the packaging material, and is released to the product by a migration process; (iii) the antioxidant compound is immobilized in the surface of the package; and (iv) the package material has inherent antioxidant and also antimicrobial activity.

Ayala-Zavala et al. (2008a) described a cyclodextrin-essential oils microcapsule that was used as a headspace artifact of the package to increase the shelf-life of fresh-cut produce. In this study it was hypothesized that internal moisture can be the driving force that released the antimicrobial compound from the complex. Ayala-Zavala et al. (2008a) established that when a molecular complex between a cyclodextrin and an antimicrobial compound in contact with water molecules, complex interactions are weakened and the active compound is released into the environment. This mechanism can be used to generate antioxidant releasing device not only to protect the food, but also to increase the nutritional and antioxidant potential of fruits, in addition to adding flavor (in the case of essential oils). This is an important establishment to be seriously considered for application in the new generation of active packaging that improves the antioxidant potential and nutritional characteristics of fruits and vegetables and thus to promote health benefits to consumers.

In summary, biopolymer-based structured delivery systems have tremendous potential to improve the nutritional status of fruits and vegetables. The challenge to food scientists is to develop simple methods to produce these systems, and moreover, look for new practical applications. Moreover, delivery systems should be capable to carry high concentrations of the delivered compounds. Furthermore, combination of systems is also a possibility in order to increase the positive effect in fresh produce. Edible coatings can be a feasible way of improving microbial stability and antioxidant content of fresh-cut fruits and vegetables, thus extending their shelf-life and promote health benefit to consumers. In addition, edible films and coatings offer opportunities to reduce the need for synthetic packaging materials and improve their recyclability. A new generation of edible coatings is being currently developed, allowing the

incorporation of active compounds using nanotechnological solutions like nanoencapsulation and emulsions. Nowadays, nanotechnologies are being used to enhance the nutritional status of food. Incorporation of active ingredients into edible coatings for fresh-cut fruits is feasible through microencapsulation solutions or the use of novel methods. Finally, such systems must be economical using production processes that are generally available in the food industries such as various mixing/ blending processes.

Conclusions and remarks

Fruits and vegetables antioxidants during storage are subject to qualitative and quantitative changes which in some cases are negative. Postharvest treatments and technological strategies (ultraviolet light, controlled and modified atmospheres, heat treatments, application of the natural compounds edible coatings, active packaging, microencapsulation and nanoemulsion) show positive and promising results to protect the antioxidant stability and ensure fruit and vegetable antioxidant potential. The application of this knowledge offers other options to deliver health benefits to consumer.

More research on fruits and vegetables is still needed to obtain data on the overall effect of postharvest treatments on the nutritional value. Investigation on the processes describing the correlation between the physiology, biochemistry and nutritional induction by postharvest treatments is needed. Although physiological mechanisms of stress tolerance are relatively well understood, further studies are essential to determine the factors that modulate plant tissue stress response as well as the possible interaction between different stresses and the response of the tissue.

Future research on encapsulation or biopolymers delivery systems should focus on developing new methods for fabrication and refining or adapting current methods for their application to fresh produce. Since many of the methods used to create delivery systems have been developed by other industries such as pharmaceuticals and polymers, it is imperative that these methods be adapted so that only food-grade ingredients and economical processes are used. As for the development of new techniques, advances in this area will likely come from a more fundamental understanding of biopolymer structure and interactions with antioxidants.

Finally, it is recommended to investigate the interaction and combination of postharvest treatments with those technological strategies that ensure and promote the antioxidant potential of fresh fruits and vegetables.

References

- Almeida, J. S., Jezur, L., Fontana, M. C., Paese, K., Silva, C. B., Pohlmann, A. R., et al. (2009). Oil-based nanoparticles containing alternative vegetable oils (grape seed oil and almond kernel oil): preparation and characterization. *Lat. Am. J. Pharm.* **28**(2): 165-172.
- Almeida, J. S., Lima, F., Ros, S. D., Bulhões, L. O. S., de Carvalho, L. M., & Beck, R. C. R. (2010). Nanostructured systems containing rutin: *in vitro* antioxidant activity and photostability studies. *Nanoscale Research Letters*. **5**(10): 1603-1610.
- Allothman, M., Bhat, R., & Karim, A. (2009a). Effects of radiation processing on phytochemicals and antioxidants in plant produce. *Trends Food Sci. Technol.* **20**(5): 201-212.
- Allothman, M., Bhat, R., & Karim, A. (2009b). UV radiation-induced changes of antioxidant capacity of fresh-cut tropical fruits. *Innovative Food Science & Emerging Technologies*, **10**(4): 512-516.
- Appendini, P., & Hotchkiss, J. H. (2002). Review of antimicrobial food packaging. *Innovative Food Science & Emerging Technologies*. **3**(2): 113-126.
- Ayala-Zavala, J. F., del Toro-Sanchez, L., Alvarez-Parrilla, E., Soto-Valdez, H., Martin-Belloso, O., Ruiz-Cruz, S., et al. (2008a). Natural antimicrobial agents incorporated in active packaging to preserve the quality of fresh fruits and vegetables. *Stewart Postharvest Review*. **4**(3): 1-9.
- Ayala-Zavala, J. F., & Gonzalez-Aguilar, G. A. (2009). Use of additives to preserve the quality of fresh-cut fruits and vegetables *Advances in Fresh-Cut Fruits and Vegetables Processing* (pp. 231): CRC.

- Ayala-Zavala, J. F., & Gonzalez-Aguilar, G. A. (2010). Optimizing the use of garlic oil as antimicrobial agent on fresh cut tomato through a controlled release system. *J. Food Sci.* **75**(5): M398-M405.
- Ayala-Zavala, J. F., Gonzalez-Aguilar, G. A., & Del Toro-Sanchez, L. (2009). Enhancing safety and aroma appealing of fresh cut fruits and vegetables using the antimicrobial and aromatic power of essential oils. *J. Food Sci.* **74**(7): R84-R91.
- Ayala-Zavala, J. F., Oms-Oliu, G., Odriozola-Serrano, I., Gonzalez-Aguilar, G. A., Alvarez-Parrilla, E., & Martin-Belloso, O. (2008b). Bio-preservation of fresh-cut tomatoes using natural antimicrobials. *Eur. Food Res. Technol.* **226**(5):1047-1055.
- Ayala-Zavala, J. F., Wang, S. Y., Wang, C. Y., & Gonzalez-Aguilar, G. A. (2004). Effect of storage temperatures on antioxidant capacity and aroma compounds in strawberry fruit. *LWT - Food Science and Technology.* **37**(7): 687-695.
- Ayala-Zavala, J. F., Wang, S. Y., Wang, C. Y., & Gonzalez-Aguilar, G. A. (2007). High oxygen treatment increases antioxidant capacity and postharvest life of strawberry fruit. *Food Technol. Biotechnol.* **45**(2): 166-173.
- Ayala Zavala, J., Del Toro Sánchez, L., Alvarez Parrilla, E., & González Aguilar, G. (2008c). High relative humidity in package of fresh cut fruits and vegetables: advantage or disadvantage considering microbiological problems and antimicrobial delivering systems? *J. Food Sci.* **73**(4): R41-R47.
- Ayranci, E., & Tunc, S. (2004). The effect of edible coatings on water and vitamin C loss of apricots (*Armeniaca vulgaris* Lam.) and green peppers (*Capsicum annuum* L.). *Food Chem.* **87**(3): 339-342.

- Azari, R., Tadmor, Y., Meir, A., Reuveni, M., Evenor, D., Nahon, S., et al. (2010). Light signaling genes and their manipulation towards modulation of phytonutrient content in tomato fruits. *Biotechnol. Adv.* **28**(1): 108-118.
- Bakowska-Barczak, A. M., & Kolodziejczyk, P. P. (2010). Black currant polyphenols: their storage stability and microencapsulation. *Industrial Crops and Products*. **34**(2): 1301-1309.
- Beckles, D. M. (2012). Factors affecting the postharvest soluble solids and sugar content of tomato (*Solanum lycopersicum* L.) fruit. *Postharvest Biol. Technol.* **63**(1): 129-140.
- Biglari, F., AlKarkhi, A. F. M., & Easa, A. M. (2009). Cluster analysis of antioxidant compounds in dates (*Phoenix dactylifera*): effect of long-term cold storage. *Food Chem.* **112**(4). 998-1001.
- Bourtoom, T. (2008). Edible films and coatings: characteristics and properties. *International Food Research Journal*. **15**(3): 237-248.
- Burin, V. M., Rossa, P. N., Ferreira-Lima, N. E., Hillmann, M. C. R., & Boirdignon-Luiz, M. T. (2011). Anthocyanins: optimisation of extraction from cabernet sauvignon grapes, microcapsulation and stability in soft drink. *Int. J. Food Sci. Tech.* **46**(1): 186-193.
- Cai-yuan, Y., Hui, Y., Xi-jiang, J., & Rui, W. (2004). The preparation method and technology of phospholipid microencapsulation. *Journal of Chemical Engineering of Chinese Universities*, 6.
- Cao, S., Zheng, Y., Wang, K., Rui, H., & Tang, S. (2010). Effect of methyl jasmonate on cell wall modification of loquat fruit in relation to chilling injury after harvest. *Food Chem.* **118**(3): 641-647.

- Cohen, S., & Flescher, E. (2009). Methyl jasmonate: A plant stress hormone as an anti-cancer drug. *Phytochemistry*. **70**(13-14): 1600-1609.
- Cordenunsi, B. R., Genovese, M. I., Oliveira-do Nascimento, J. R., Aymoto-Hassimotto, N. M., Jose-dos Santos, R., & Lajolo, F. M. (2005). Effects of temperature on the chemical composition and antioxidant activity of three strawberry cultivars. *Food Chem.* **91**(1): 113-121.
- Chan, Z. L., & Tian, S. P. (2006). Induction of H₂O₂-metabolizing enzymes and total protein synthesis by antagonistic yeast and salicylic acid in harvested sweet cherry fruit. *Postharvest Biol. Technol.* **39**(3): 314-320.
- Chanjirakul, K., Wang, S. Y., Wang, C. Y., & Siriphanich, J. (2006). Effect of natural volatile compounds on antioxidant capacity and antioxidant enzymes in raspberries. *Postharvest Biol. Technol.* **40**(2): 106-115.
- Chanjirakul, K., Wang, S. Y., Wang, C. Y., & Siriphanich, J. (2007). Natural volatile treatments increase free radical scavenging capacity of strawberries and blackberries. *J. Sci. Food Agric.* **87**(8): 1463-1472.
- Chien, P.-J., Sheu, F., & Lin, H.-R. (2007). Quality assessment of low molecular weight chitosan coating on sliced red pitayas. *J. Food Eng.* **79**(2): 736-740.
- de la Peña-Moreno, F., Blanch, G. P., Flores, G., & Ruiz del Castillo, M. L. (2010b). Impact of postharvest methyl jasmonate treatment on the volatile composition and flavonol content of strawberries. *J. Sci. Food Agric.* **90**(6): 989-994.

- de la Peña-Moreno, F., Blanch, G. P., & Ruiz-del Castillo, M. L. (2010a). (+)-Methyl jasmonate-induced bioformation of myricetin, quercetin and kaempferol in red raspberries. *J. Agric. Food Chem.* **58**(22): 11639-11644.
- Diaz-Mula, H. M., Zapata, P. J., Guillén, F., Martínez-Romero, D., Castillo, S., Serrano, M., et al. (2009). Changes in hydrophilic and lipophilic antioxidant activity and related bioactive compounds during postharvest storage of yellow and purple plum cultivars. *Postharvest Biol. Technol.* **51**(3): 354-363.
- Duan, X., Liu, T., Zhang, D., Su, X., Lin, H., & Jiang, Y. (2010). Effect of pure oxygen atmosphere on antioxidant enzyme and antioxidant activity of harvested litchi fruit during storage. *Food Res. Int.* **44**(7): 1905-1911.
- Faurie, B., Cluzet, S., & Merillon, J.-M. (2009). Implication of signaling pathways involving calcium, phosphorylation and active oxygen species in methyl jasmonate-induced defense responses in grapevine cell cultures. *J. Plant Physiol.* **166**(17): 1863-1877.
- Girennavar, B., Jayaprakasha, G., Mclin, S., Maxim, J., Sun Yoo, K., & Patil, B. (2008). Influence of electron-beam irradiation on bioactive compounds in grapefruits (*Citrus paradisi* Macf.). *J. Agric. Food Chem.* **56**(22): 10941-10946.
- Gonzalez-Aguilar, G., Celis, J., Sotelo-Mundo, R., De La Rosa, L., Rodrigo-Garcia, J., & Alvarez-Parrilla, E. (2008). Physiological and biochemical changes of different fresh cut mango cultivars stored at 5 °C. *Int. J. Food Sci. Tech.* **43**(1): 91-101.
- Gonzalez-Aguilar, G., Tiznado-Hernandez, M., & Wang, C. (2006). Physiological and biochemical responses of horticultural products to methyl jasmonate. *Stewart Postharvest Review.* **2**(1): 1-9.

- Gonzalez-Aguilar, G., Tiznado-Hernandez, M., & Zavaleta-Gatica, R. (2004). Methyl jasmonate treatments reduce chilling injury and activate the defense response of guava fruits. *Biochem. Biophys. Res. Commun.* **313**(3): 694-701.
- Gonzalez-Aguilar, G., Villa-Rodriguez, J., Ayala-Zavala, J., & Yahia, M.E. (2010). Improvement of the antioxidant status of tropical fruits as a secondary response to some postharvest treatments. *Trends Food Sci. Technol.* **21**(10): 475-482.
- Gonzalez-Aguilar, G., Zavaleta-Gatica, R., & Tiznado-Hernández, M. (2007). Improving postharvest quality of mango 'Haden' by UV-C treatment. *Postharvest Biol. Technol.* **45**(1): 108-116.
- Hamauzu, Y. (2006). Role and evolution of fruit phenolic compounds during ripening and storage. *Stewart Postharvest Review.* **2**(2): 1-7.
- Han, C., Zhao, Y., Leonard, S., & Traber, M. (2004). Edible coatings to improve storability and enhance nutritional value of fresh and frozen strawberries (*Fragaria ananassa*) and raspberries (*Rubus ideaus*). *Postharvest Biol. Technol.* **33**(1): 67-78.
- Han, C. R., Lederer, C., McDaniel, M., & Zhao, Y. Y. (2005). Sensory evaluation of fresh strawberries (*Fragaria ananassa*) coated with chitosan-based edible coatings. *J. Food Sci.* **70**(3): S172-S178.
- Hertog, M. G. L., Hollman, P. C. H., & Katan, M. B. (1992). Content of potentially anticarcinogenic flavonoids of 28 vegetables and 9 fruits commonly consumed in the Netherlands. *J. Agric. Food Chem.* **40**(12): 2379-2383.
- Holst, B., & Williamson, G. (2008). Nutrients and phytochemicals: from bioavailability to bioefficacy beyond antioxidants. *Curr. Opin. Biotechnol.* **19**(2): 73-82.

- Hussain, P. R., Wani, A. M., Meena, R. S., & Dar, M. A. (2010). Gamma irradiation induced enhancement of phenylalanine ammonia-lyase (PAL) and antioxidant activity in peach (*Prunus persica* Bausch, cv. Elberta). *Radiat. Phys. Chem.*, 79(9), 982-989.
- Janjarasskul, T., & Krochta, J. M. (2010). Edible packaging materials. *Annual Review of Food Science and Technology*. 1: 415-448.
- Javanmardi, J., & Kubota, C. (2006). Variation of lycopene, antioxidant activity, total soluble solids and weight loss of tomato during postharvest storage. *Postharvest Biol. Technol.* 41(2): 151-155.
- Jimenez, L., Alarcon, E., Trevithick-Sutton, C., Gandhi, N., & Scaiano, J. C. (2011). Effect of gamma-radiation on green onion DNA integrity: role of ascorbic acid and polyphenols against nucleic acid damage. *Food Chem.* 128(3): 735-741.
- Kader, A. A., & Ben-Yehoshua, S. (2000). Effects of superatmospheric oxygen levels on postharvest physiology and quality of fresh fruits and vegetables. *Postharvest Biol. Technol.* 20(1). 1-13.
- Kevers, C., Falkowski, M., Tabart, J., Defraigne, J., Dommès, J., & Pincemail, J. (2007). Evolution of antioxidant capacity during storage of selected fruits and vegetables. *J. Agric. Food Chem.* 55(21): 8596-8603.
- Kim, H. J., Fonseca, J. M., Choi, J. H., & Kubota, C. (2007). Effect of methyl jasmonate on phenolic compounds and carotenoids of romaine lettuce (*Lactuca sativa* L.). *J. Agric. Food Chem.* 55(25). 10366-10372.

- Kris-Etherton, P. M., Hecker, K. D., Bonanome, A., Coval, S. M., Binkoski, A. E., Hilpert, K. F., et al. (2002). Bioactive compounds in foods: their role in the prevention of cardiovascular disease and cancer. *The American Journal of Medicine*. 71S-88S.
- Kruger, E., Dietrich, H., Schopplein, E., Rasim, S., & Kurbel, P. (2011). Cultivar, storage conditions and ripening effects on physical and chemical qualities of red raspberry fruit. *Postharvest Biol. Technol.* **60**(1): 31-37.
- Larrosa, M., Gonzalez-Sarrias, A., Yanez-Gascon, M. J., Selma, M. V., Azorin-Ortuno, M., Toti, S., et al. (2010). Anti-inflammatory properties of a pomegranate extract and its metabolite urolithin-A in a colitis rat model and the effect of colon inflammation on phenolic metabolism. *Journal of Nutritional Biochemistry*. **21**(8): 717-725.
- Leja, M., Mareczek, A., & Ben, J. (2003). Antioxidant properties of two apple cultivars during long-term storage. *Food Chem.* **80**(3): 303-307.
- Lin, D., & Zhao, Y. (2007). Innovations in the development and application of edible coatings for fresh and minimally processed fruits and vegetables. *Comprehensive Reviews in Food Science and Food Safety*. **6**(3): 60-75.
- Liu, C., Han, X., Cai, L., Lu, X., Ying, T., & Jiang, Z. (2011). Postharvest UV-B irradiation maintains sensory qualities and enhances antioxidant capacity in tomato fruit during storage. *Postharvest Biol. Technol.* **59**(3): 232-237.
- Lotito, S. B., Zhang, W.-J., Yang, C. S., Crozier, A., & Frei, B. (2011). Metabolic conversion of dietary flavonoids alters their anti-inflammatory and antioxidant properties. *Free Radical Biol. Med.* **51**(2): 454-463.

- Lu, F., Ye, X., & Liu, D. (2009). Review of antimicrobial food packaging. *Transactions of the Chinese Society of Agricultural Machinery*. **40**(6): 138-142.
- Madene, A., Jacquot, M., Scher, J., & Desobry, S. (2006). Flavour encapsulation and controlled release - a review. *Int. J. Food Sci. Technol.* **41**(1): 1-21.
- Manjunatha, G., Lokesh, V., & Neelwarne, B. (2010). Nitric oxide in fruit ripening: Trends and opportunities. *Biotechnol. Adv.* **28**(4): 489-499.
- Martin-Belloso, O., Rojas-Graü, M. A., & Soliva-Fortuny, R. (2009). Delivery of flavor and active Ingredients using edible films and coatings. In M. Embuscado & K. Huber (Eds.), *Edible Films and Coatings for Food Applications* (pp. 295-313): Springer Verlag.
- Matalanis, A., Jones, O. G., & McClements, D. J. (2011). Structured biopolymer-based delivery systems for encapsulation, protection, and release of lipophilic compounds. *Food Hydrocolloids*. **25**(8): 1865-1880.
- Maul, P., McCollum, G., Guy, C. L., & Porat, R. (2011). Temperature conditioning alters transcript abundance of genes related to chilling stress in 'Marsh' grapefruit flavedo. *Postharvest Biol. Technol.* **60**(3): 177-185.
- Mei, Y., Zhao, Y., Yang, J., & Furr, H. (2002). Using edible coating to enhance nutritional and sensory qualities of baby carrots. *J. Food Sci.* **67**(5): 1964-1968.
- Meng, X., Han, J., Wang, Q., & Tian, S. (2009). Changes in physiology and quality of peach fruits treated by methyl jasmonate under low temperature stress. *Food Chem.* **114**(3): 1028-1035.

- Mirdehghan, S., Rahemi, M., Serrano, M., Guillén, F., Martínez-Romero, D., & Valero, D. (2007). The application of polyamines by pressure or immersion as a tool to maintain functional properties in stored pomegranate arils. *J. Agric. Food Chem.* **55**(3): 755-760.
- Montero-Calderon, M., Rojas-Grau, M. A., Aguilo-Aguayo, I., Soliva-Fortuny, R., & Martin-Belloso, O. (2010). Influence of modified atmosphere packaging on volatile compounds and physicochemical and antioxidant attributes of fresh-cut pineapple (*Ananas comosus*). *J. Agric. Food Chem.* **58**(8): 5042-5049.
- Mozafari, M. R., Flanagan, J., Matia-Merino, L., Awati, A., Omri, A., Suntres, Z. E., et al. (2006). Recent trends in the lipid-based nanoencapsulation of antioxidants and their role in foods. *J. Sci. Food Agric.* **86**(13): 2038-2045.
- Nik, A. M., Corredig, M., & Wright, A. J. (2011). Release of lipophilic molecules during in vitro digestion of soy protein-stabilized emulsions. *Mol. Nutr. Food Res.* **55**: S278-289.
- Niyogi, K. K. (1999). Photoprotection revisited: genetic and molecular approaches. *Annu. Rev. Plant Biol.* **50**(1): 333-359.
- Odriozola-Serrano, I., Oms-Oliu, G., Soliva-Fortuny, R., & Martin-Belloso, O. (2009). Effect of high-oxygen atmospheres on the antioxidant potential of fresh-cut tomatoes. *J. Agric. Food Chem.*, **57**(15): 6603-6610.
- Oms-Oliu, G., Soliva-Fortuny, R., & Martín-Belloso, O. (2008). Edible coatings with antibrowning agents to maintain sensory quality and antioxidant properties of fresh-cut pears. *Postharvest Biol. Technol.*, **50**(1): 87-94.
- Ozdemir, M., & Floros, J. D. (2004). Active food packaging technologies. *Crit. Rev. Food Sci. Nutr.*, **44**(3): 185-193.

- Palafox-Carlos, H., Ayala-Zavala, J. F., & Gonzalez-Aguilar, G. A. (2011). The role of dietary fiber in the bioaccessibility and bioavailability of fruit and vegetable antioxidants. *J. Food Sci.* **76**(1): R6-R15.
- Piljac-Zegarac, J., & Samec, D. (2010). Antioxidant stability of small fruits in postharvest storage at room and refrigerator temperatures. *Food Res. Int.* **44**(1): 345-350.
- Ponce, A. G., Roura, S. I., del Valle, C. E., & Moreira, M. R. (2008). Antimicrobial and antioxidant activities of edible coatings enriched with natural plant extracts: *in vitro* and *in vivo* studies. *Postharvest Biol. Technol.* **49**(2): 294-300.
- Quintanilla-Carvajal, M. X., Camacho-Diaz, B. H., Meraz-Torres, L. S., Chanona-Perez, J. J., Alamilla-Beltran, L., Jimenez-Aparicio, A., et al. (2010). Nanoencapsulation: a new trend in food engineering processing. *Food Engineering Reviews.* **2**(1): 39-50.
- Rawson, A., Patras, A., Tiwari, B. K., Noci, F., Koutchma, T., & Brunton, N. (2011). Effect of thermal and non thermal processing technologies on the bioactive content of exotic fruits and their products: review of recent advances. *Food Res. Int.* **44**(7): 1875-1887.
- Reyes, L. F., & Cisneros-Zevallos, L. (2007). Electron-beam ionizing radiation stress effects on mango fruit (*Mangifera indica* L.) antioxidant constituents before and during postharvest storage. *J. Agric. Food Chem.* **55**(15): 6132-6139.
- Ribeiro, C., Vicente, A. A., Teixeira, J. A., & Miranda, C. (2007). Optimization of edible coating composition to retard strawberry fruit senescence. *Postharvest Biol. Technol.* **44**(1): 63-70.

- Rojas-Grau, M. A., Soliva-Fortuny, R., & Martin-Belloso, O. (2009). Edible coatings to incorporate active ingredients to fresh-cut fruits: a review. *Trends Food Sci. Technol.* **20**(10): 438-447.
- Rudell, D. R., & Mattheis, J. P. (2008). Synergism exists between ethylene and methyl jasmonate in artificial light-induced pigment enhancement of 'Fuji' apple fruit peel. *Postharvest Biol. Technol.* **47**(1): 136-140.
- Saenz, C., Tapia, S., Chavez, J., & Robert, P. (2009). Microencapsulation by spray drying of bioactive compounds from cactus pear (*Opuntia ficus-indica*). *Food Chem.* **114**(2): 616-622.
- Serrano, M., Martínez-Romero, D., Guillen, F., Valverde, J. M., Zapata, P. J., Castillo, S., et al. (2008). The addition of essential oils to MAP as a tool to maintain the overall quality of fruits. *Trends Food Sci. Technol.* **19**(9): 464-471.
- Shin, Y., Liu, R. H., Nock, J. F., Holliday, D., & Watkins, C. B. (2007). Temperature and relative humidity effects on quality, total ascorbic acid, phenolics and flavonoid concentrations and antioxidant activity of strawberry. *Postharvest Biol. Technol.* **45**: 349-357.
- Shin, Y., Ryu, J. A., Liu, R. H., Nock, J. F., & Watkins, C. B. (2008). Harvest maturity, storage temperature and relative humidity affect fruit quality, antioxidant contents and activity, and inhibition of cell proliferation of strawberry fruit. *Postharvest Biol. Technol.* **49**(2): 201-209.
- Shu, B., Yu, W., Zhao, Y., & Liu, X. (2006). Study on microencapsulation of lycopene by spray-drying. *J. Food Eng.* **76**(4): 664-669.

- Simões, A. D. N., Allende, A., Tudela, J. A., Puschmann, R., & Gil, M. I. (2011). Optimum controlled atmospheres minimise respiration rate and quality losses while increase phenolic compounds of baby carrots. *LWT - Food Science and Technology*. **44**(1): 277-283.
- Simões, A. D. N., Tudela, J. A., Allende, A., Puschmann, R., & Gil, M. I. (2009). Edible coatings containing chitosan and moderate modified atmospheres maintain quality and enhance phytochemicals of carrot sticks. *Postharvest Biol. Technol.* **51**(3): 364-370.
- Singh, S., & Pal, R. (2008). Controlled atmosphere storage of guava (*Psidium guajava* L.) fruit. *Postharvest Biol. Technol.* **47**(3): 296-306.
- Takahashi, M., Uechi, S., Takara, K., Asikin, Y., & Wada, K. (2009). Evaluation of an oral carrier system in Rats: Bioavailability and Antioxidant Properties of liposome-encapsulated curcumin. *J. Agric. Food Chem.* **57**(19): 9141-9146.
- Tapia, M., Rodriguez, F., Rojas-Graü, M., & Martin-Belloso, O. (2005). *Formulation of alginate and gellan based edible coatings with antioxidants for fresh-cut apple and papaya*. Paper presented at the IFT annual meeting, New Orleans, Louisiana.
- Tapia, M. S., Rojas-Graue, M. A., Carmona, A., Rodriguez, F. J., Soliva-Fortuny, R., & Martin-Belloso, O. (2008). Use of alginate and gellan-based coatings for improving barrier, texture and nutritional properties of fresh-cut papaya. *Food Hydrocolloids*. **22**(8): 1493-1503.
- Thomas, P., & Bramlage, W. J. (1986). Radiation preservation of foods of plant origin. Part IV. Subtropical fruits: citrus, grapes, and avocados. *Critical Reviews in Food Science & Nutrition*. **24**(1): 53-89.

- Thomas, P., & Diehl, J. (1988). Radiation preservation of foods of plant origin. Part VI. Mushrooms, tomatoes, minor fruits and vegetables, dried fruits, and nuts. *Critical Reviews in Food Science & Nutrition*. **26**(4): 313-358.
- Thomas, P., & Moy, J. H. (1986). Radiation preservation of foods of plant origin. III. Tropical fruits: bananas, mangoes, and papayas. *Critical Reviews in Food Science & Nutrition*. **23**(2): 147-205.
- Thomas, P., & Sparks, W. C. (1984). Radiation preservation of foods of plant origin. Part 1. Potatoes and other tuber crops. *Critical Reviews in Food Science & Nutrition*. **19**(4): 327-379.
- Tulipani, S., Llorach, R., Jauregui, O., Lopez-Uriarte, P., Garcia-Aloy, M., Bullo, M., et al. (2011). Metabolomics Unveils Urinary Changes in Subjects with Metabolic Syndrome following 12-Week Nut Consumption. *Journal of Proteome Research*. **10**(11): 5047-5058.
- Vargas, M., Albors, A., Chiralt, A., & Gonzalez-Martinez, C. (2006). Quality of cold-stored strawberries as affected by chitosan-oleic acid edible coatings. *Postharvest Biol. Technol.* **41**(2): 164-171.
- Variyar, P. S., Limaye, A., & Sharma, A. (2004). Radiation-induced enhancement of antioxidant contents of soybean (*Glycine max* Merrill). *J. Agric. Food Chem.* **52**(11): 3385-3388.
- Vezzulli, S., Civardi, S., Ferrari, F., & Bavaresco, L. (2007). Methyl jasmonate treatment as a trigger of resveratrol synthesis in cultivated grapevine. *American Journal of Enology and Viticulture*. **58**(4): 530-533.

- Vicente, A. R., Manganaris, G. A., Sozzi, G. O., & Crisosto, C. H. (2009). Nutritional quality of fruits and vegetables. *Postharvest Handling: A Systems Approach (Food Science and Technology)*. 58-106.
- Villa-Rodriguez, J., Molina-Corral, F., Ayala-Zavala, J., Olivas, G. I., & Gonzalez-Aguilar, G. (2011). Effect of maturity stage on the content of fatty acids and antioxidant activity of 'Hass' avocado. *Food Res. Int.* **44**(5): 1231-1237.
- Visioli, F., Alarcon De La Lastra, C., Andres-Lacueva, C., Aviram, M., Calhau, C., Cassano, A., et al. (2011). Polyphenols and Human Health: A Prospectus. *Crit. Rev. Food Sci. Nutr.*, **51**(6): 524-546.
- Wang, B., Wang, J., Liang, H., Yi, J., Zhang, J., Lin, L., et al. (2008). Reduced chilling injury in mango fruit by 2, 4-dichlorophenoxyacetic acid and the antioxidant response. *Postharvest Biol. Technol.* **48**(2): 172-181.
- Wang, C., & Buta, J. (1994). Methyl jasmonate reduces chilling injury in Cucurbita pepo through its regulation of abscisic acid and polyamine levels. *Environ. Exp. Bot.* **34**(4): 427-432.
- Wang, J., Cao, Y., Sun, B., & Wang, C. (2011). Physicochemical and release characterisation of garlic oil- β -cyclodextrin inclusion complexes. *Food Chem.* **127**(4): 1680-1685.
- Wang, K., Jin, P., Cao, S., Shang, H., Yang, Z., & Zheng, Y. (2009). Methyl jasmonate reduces decay and enhances antioxidant capacity in chinese bayberries. *J. Agric. Food Chem.* **57**(13): 5809-5815.
- Wang, S., & Chen, C. (2010). Effect of allyl isothiocyanate on antioxidant enzyme activities, flavonoids and post-harvest fruit quality of blueberries (*Vaccinium corymbosum* L., cv. Duke). *Food Chem.* **122**(4): 1153-1158.

- Wang, S. Y., Bowman, L., & Ding, M. (2008). Methyl jasmonate enhances antioxidant activity and flavonoid content in blackberries (*Rubus* sp.) and promotes antiproliferation of human cancer cells. *Food Chem.* **107**(3): 1261-1269.
- Wang, S. Y., Chen, C. T., & Yin, J. J. (2010). Effect of allyl isothiocyanate on antioxidants and fruit decay of blueberries. *Food Chem.* **120**(1): 199-204.
- Xiaomei, L. Y. F. T. L., & Yuefeng, C. (2009). Extraction and microencapsulation of grape seed oil *Journal of the Chinese Cereals and Oils Association.* **1**: 23-29.
- Yahia, E. M. (2009). *Modified and Controlled Atmospheres for the Storage, Transportation, and Packaging of Horticultural Commodities* (1ra ed.). Boca Raton: CRC press.
- Yahia, E. M. (2010). The contribution of fruits and vegetables consumption to human health. In G. A. Gonzalez-Aguilar, E. Alvarez-Parrilla & L. de la Rosa (Eds.), *Fruit and Vegetable Phytochemicals: chemistry, nutritional and stability* (pp. 3-52). Iowa: Wiley-Blackwell.
- Yang, Z., Zheng, Y., & Cao, S. (2008). Effect of high oxygen atmosphere storage on quality, antioxidant enzymes, and DPPH-radical scavenging activity of chinese bayberry fruit. *J. Agric. Food Chem.* **57**(1): 176-181.
- Zhang, X., Sheng, J., Li, F., Meng, D., & Shen, L. (2012). Methyl jasmonate alters arginine catabolism and improves postharvest chilling tolerance in cherry tomato fruit. *Postharvest Biol. Technol.* **64**(1): 160-167.

Figures captions

Fig. 1 Fruits and vegetables responses to abiotic postharvest stresses (postharvest treatments). Postharvest stress signals trigger the downstream signaling process which activate stress-responsive mechanisms to re-establish homeostasis and protect and repair biomolecules. In this sense, postharvest stress can activate enzymatic and non-enzymatic antioxidant system of the fresh produce contributing to an adaptation process to stressful conditions and subsequently the maintenance of fruit quality and better antioxidant potential. Nevertheless, inadequate postharvest doses result in an irreversible change of cellular homeostasis leading lower overall quality of the fruits and vegetables treated.

Fig. 2 Edible coating containing antioxidants along the film covering the fresh produce. Several antioxidant compounds may be incorporated into the coating: (I) phenolic compounds, (II) β -carotene, (III) α -tocopherol, (IV) ascorbic acid, etc.

Fig. 3 Active packagings deliver antioxidants into the package atmosphere of fresh produce. Several antioxidant compounds may be incorporated by different concepts: (I) Sachets, (II) within the packaging matrix and (III) immobilized in the surface of the package.

Fig. 4 Emulsion structure for protection and delivery of hydrophobic antioxidants such (I) β -carotene and (II) α -tocopherol, among others.

Fig. 5 Microencapsulation structure for protection and delivery mostly of hydrophilic antioxidants such (I) ascorbic acid and (II) phenolic compounds among others.

Fig. 1

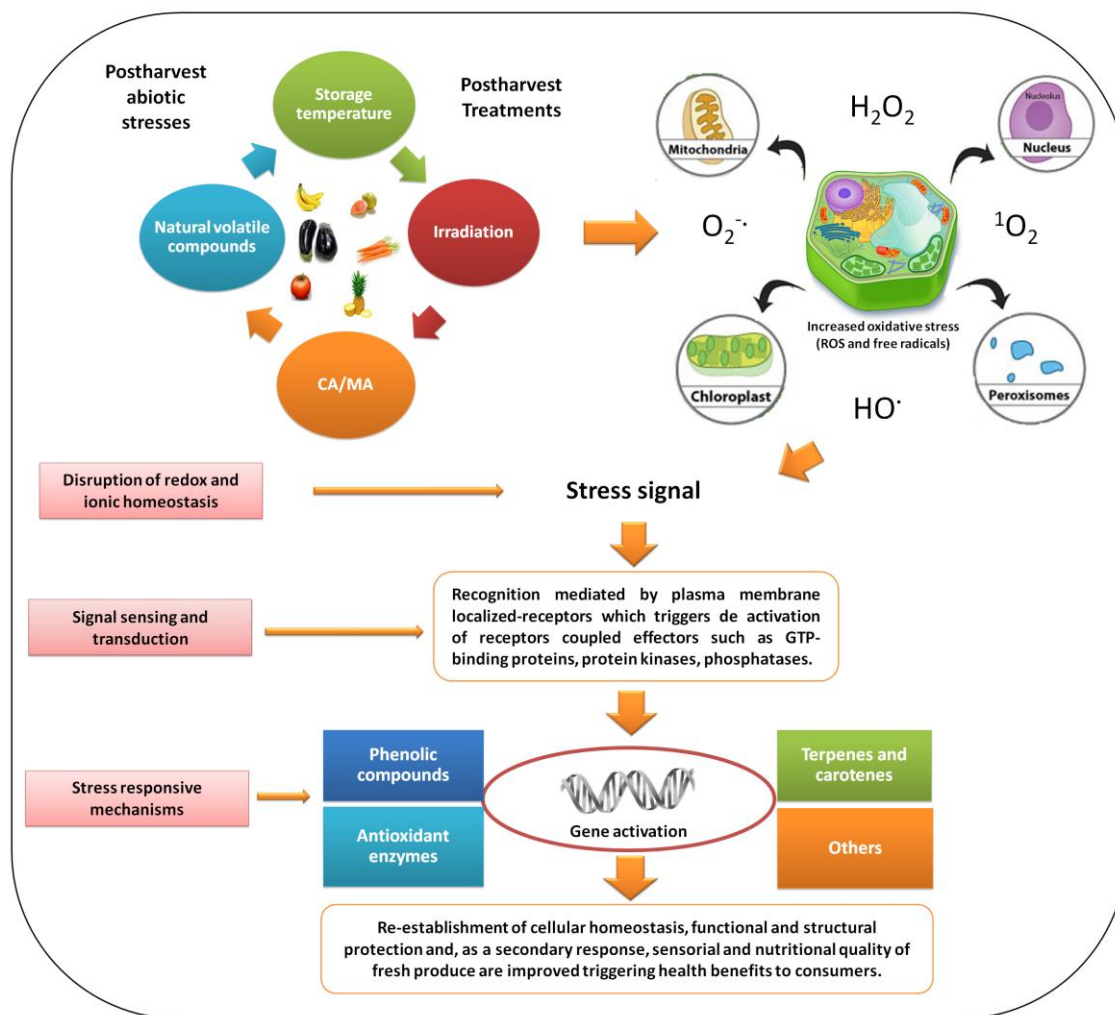


Fig. 2

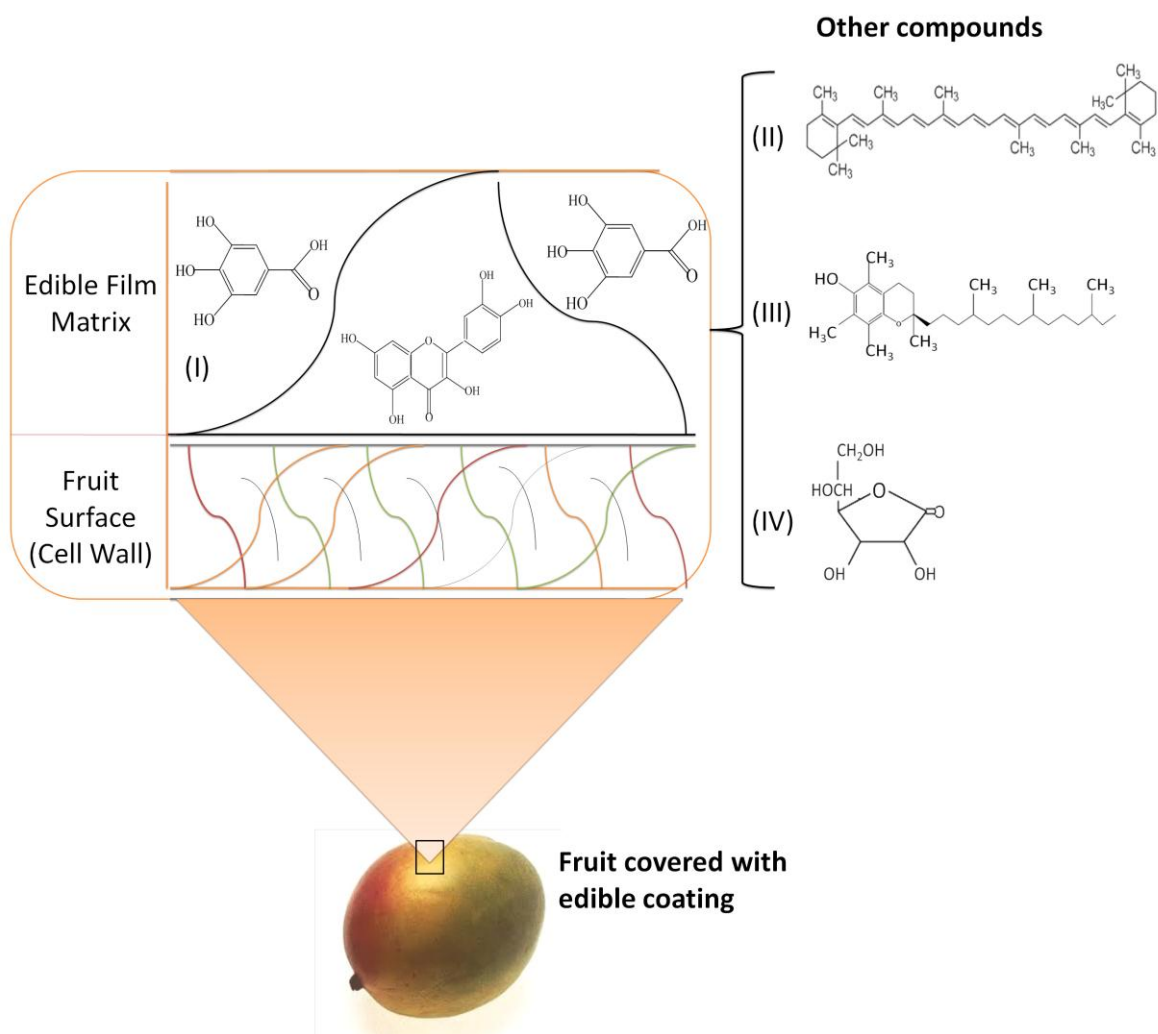


Fig. 3

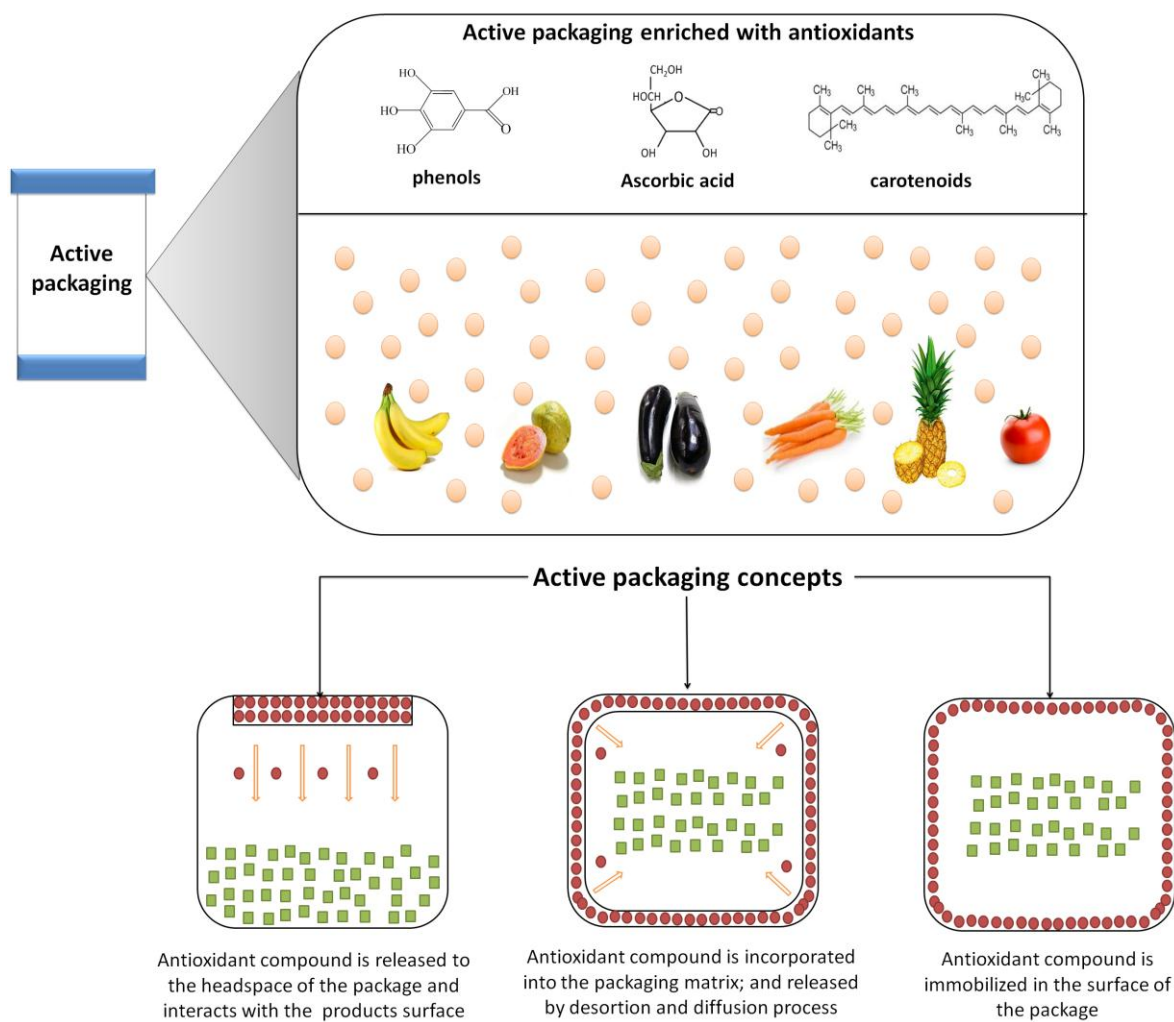


Fig. 4

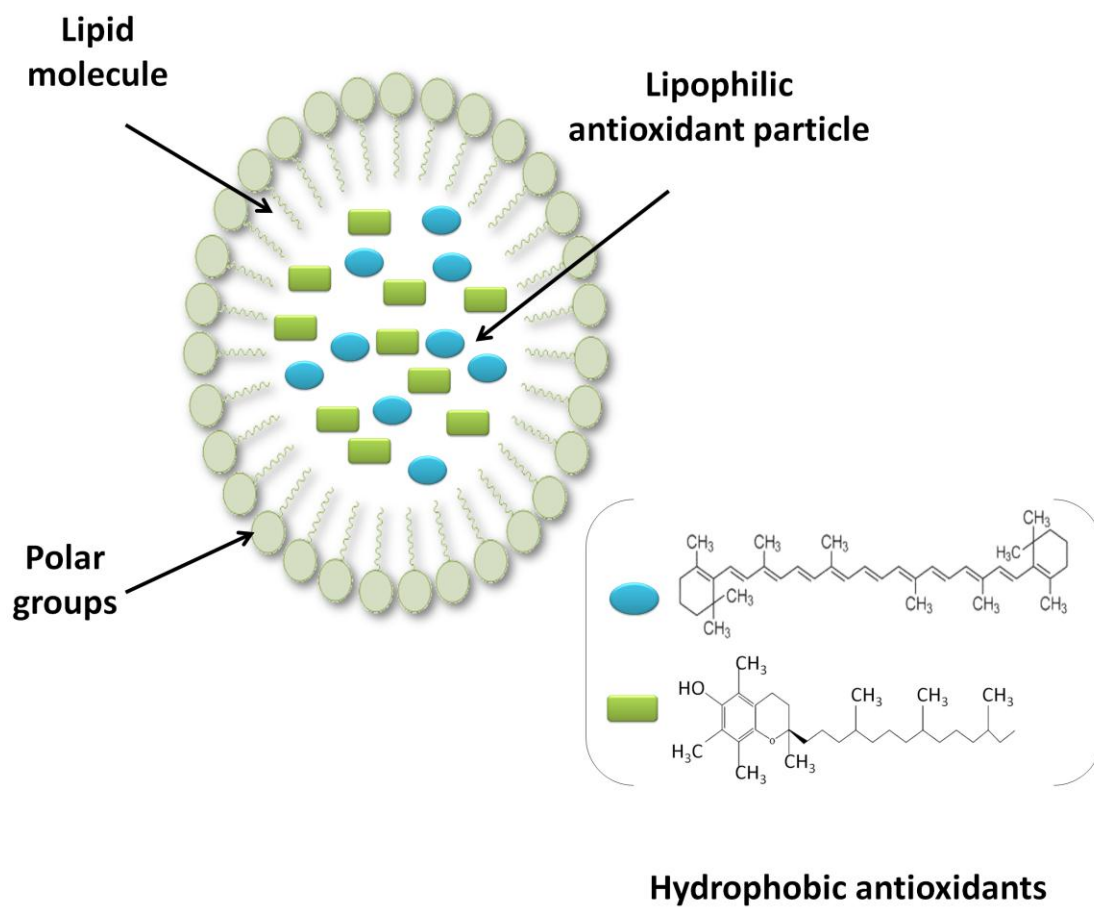


Fig. 5

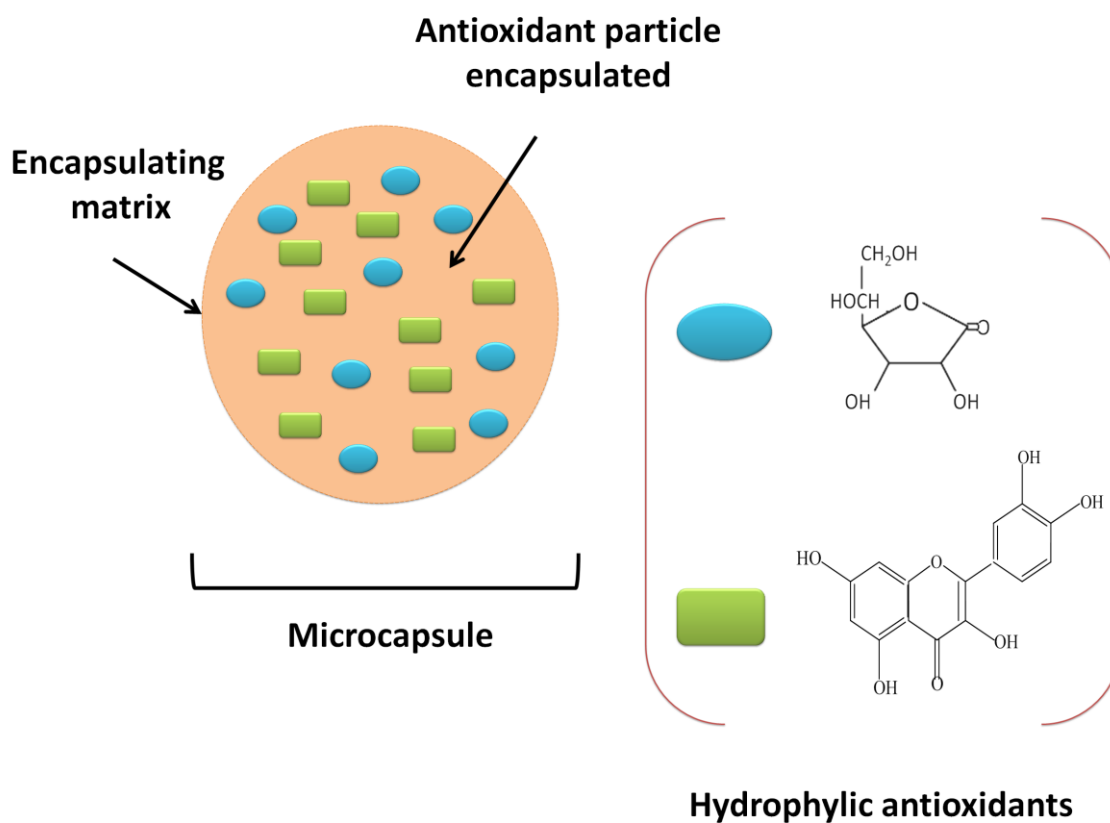


Table 1. Current studies about the effects of ionizing irradiation on antioxidants in some fruits and vegetables

| Produce | Irradiation source and doses | Storage conditions | Results | Reference |
|-------------------------------------------------------------------|------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| Green onion (<i>Allium wakegi</i>) | γ -irradiation (1.2 kGy) | After the treatment, fruits were stored at -80 °C | An increase on TP content was observed but the treatment reduced the AOC and ascorbic acid content around 40 % | (Jimenez et al., 2011) |
| Brazilian mushroom (<i>Agaricus blazei</i>) | γ -irradiation (2.5, 10, 15 and 20 kGy) | 4 ± 1 °C, 90 % RH | No general trend for effects on TP was observed in the doses applied. There was a decrement in the content of ascorbic acid with increased doses. However, doses of γ -irradiation between 2.5 and 20 kGy increased the AOC of the extracts | (Jiang et al., 2010) |
| Peach (<i>Prunus persica Bausch</i> cv. Alberta) | γ -irradiation (1-2 kGy) | 3 ± 1 °C, 80 % RH during 28 days | Doses between 1.6-2 kGy showed an increase in AOC, TP, TA and PAL activity but the ascorbic acid content was affected negatively | (Hussain et al., 2010) |
| Baby leaf spinach (<i>Spinacia oleracea</i> cv Lazio and Samish) | γ -irradiation (0.5, 1, 1.5 and 2 kGy) | After the treatments, leaf tissue were stored at -80 °C | Ascorbic acid and carotenoids were reduced at 2 kGy but it was observed differences among cultivars at lesser doses of 0.5 and 1.5 kGy on the content of these compounds tocopherol content was not affected | (Lester and Hallman., 2010) |

by any dose.

| | | | | |
|-------------------------------------------------|----------------------------------------------------|------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|
| Kiwi (<i>Actinidia deliciosa</i> cv. Hayward) | γ -irradiation (1, 2 and 3 kGy) | 20 ± 2 °C during 21 days | No changes were observed on the carotenoid content but treatment had a negative effect on ascorbic acid and AOC with doses up to 1 kGy | (Hee-Kim et al., 2009) |
| Grapefruits (<i>citrus paradise Macf</i>) | Electron beam (1, 2.5, 5 and 10 kGy) | Fruits were juiced after irradiation treatment and stored at -80 °C until analysis | There was a decrease on ascorbic acid, lycopene and nomilin in doses beyon to 1 kGy. An increase on β -carotene and naringin was found at doses beyon to 1 kGy. | (Girenavvar et al., 2008) |
| Mango (<i>Mangifera indica</i> L.) | Electron beam (1, 1.5 and 3.1 kGy) | 15 °C during 18 days | TP were not affected while ascorbic ascorbic acid decreased around 50-54 % Also, the biosynthesis of carotenoids were affected by the treatment | (Reyes and Cisneros-Cevallos 2007) |
| Apricot (<i>Prunus armeniaca</i> L cv. Búlida) | Electron beam (0.5 and 1 kGy) | 2 °C during 13 days and kept 48 h at 20 °C before the analysis | There was no effect of treatment in the content of total carotenoids compared to untreated fruits | (Egea et al., 2007) |
| Rosemary leaf extracts | γ -irradiation (30 kGy) | | γ -irradiation increased by 35% the TP content and this increase correlated with total AOC | (Pérez et al., 2007) |
| Black pepper (<i>Piper nigrum</i> L.) | γ -irradiation (5, 7.5, 10, 20, and 30 kGy) | 5 months | Irradiated black pepper showed better AOC compared with non-treated peppers during 2 months of storage | (Suhaj et al., 2006) |

| | | | | |
|--------------------------------------------------------------|--------------------------------------------|-------------------|-----------------------------------------------------------------------------------------------------------------------|-------------|
| Fresh-cut vegetables (Romaine, iceberg lettuce endive) | γ -irradiation (0.5, 1 and 2 kGy | 7–8 °C for 8 days | γ -irradiation treatment (0, 0.5, 1, and 2 kGy) showed a significant increase in the TP content and AOC. | (Fan, 2005) |
|--------------------------------------------------------------|--------------------------------------------|-------------------|-----------------------------------------------------------------------------------------------------------------------|-------------|

Table 2. Current studies about the effects of non-ionizing irradiation on antioxidants in some fruits and vegetables

| Produce | Irradiation source and doses | Storage conditions | Results | Reference |
|-------------------------------------------------------|----------------------------------------------------|----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|
| Red peppers (<i>Capsicum annuum</i> L cv Cornago) | UV-C (10 and 20 kJ/m ²) | 0 °C for 21 days | UV-C irradiation did not alter carotenoid content and AOC while ascorbic acid was slightly higher in the treated produce | (Andrade-Cuvi., 2011) |
| Fresh-cut mushrooms (<i>Agaricus bisporus</i>) | Pulsed light (4.8, 12 and 24 Jcm ⁻²) | 5 °C for 15 days | There was a decrease on the content of ascorbic acid, TP and AOC in all of the treatments regards to control | (Oms-oliu et al., 2011) |
| Tomatoe (<i>Lycopersicon esculentum</i> cv. Zhenfen) | UV-B (10, 20, 40 and 80 kJ/m ²) | 14 °C, 95% RH in dark | 20 or 40 kJ/m ² promoted the accumulation of TP, TF and enhanced AOC during storage. | (Liu et al., 2011) |
| Onion (<i>Illium cepa</i> L) | UV-C (2.5, 5, 10, 20 and 40 kJ m ²) | 2 °C, 65 % RH for 7 months | 20 and 40 kJm ² increase the content of total flavonols, TA in a profitable manner | (Rodrigues et al., 2010) |
| Fresh-cut tropical fruits | UV-C (2.158 Jm ² during 10, 20, 30 min) | 24 ± 1 ° C for 30 min | TP and TF increased as well as AOC with the increase in treated time. However, a decrease in ascorbic acid was observed in all the treatments | (Alothman et al., 2009) |

| | | | | |
|-------------------------------------------------------------------|----------------------------------------------------|--------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|
| blueberries (<i>Vaccinium corymbosum</i> L.) | UV-C (0.43, 2.15, 4.30 and 6.45 kJm ²) | After the treatment, samples were stored at -80 °C | The optimum doses of UV-C for enhancing TP and anthocyanins were 2.15 and 4.30 kJ m ² | (Wang et al., 2009a) |
| Blueberry (<i>Vaccinium corymbosum</i> cv. Collins and Bluecrop) | UV-C (1, 2 and 4 kJm ²) | 5 °C for 7 days, then transferred to 20 °C for 2 days. | TP, TA and AOC increased at a dose of 1 kJm ² in blueberry "Collins". In blueberry "Bluecrop" TA and AOC increased with treatment intensity, but no clear effects were seen in TP | (Perkins-Veazie et al., 2008) |
| Fresh-cut Mangoes (<i>Mangifera indica</i> L.) | UV-C (15 watt G15 T8) | 24 ± 1 °C for 15 days | Fruits exposed to UV-C for 10 min showed an increase in TP, TF and AOC. However a decrease in Ascorbic acid and β-carotene was observed | (Gonzalez-Aguilar et al., 2007a) |
| Mango (<i>Mangifera indica</i> L. cv Haden) | UV-B (70, 200, 400 and 700 Gy) | 25 °C for 18 days | Exposure to 2.46 and 4.93 kJ m ² increased TP and TF content | (Gonzalez-Aguilar et al., 2007) |
| Brocoli (<i>Brassica oleracea</i> cv. Italica) | UV-C (8 kJ m ⁻²) | 4 °C during 21 days | Exposure to UV-C increased TP ascorbic acid content and AOC | (Lemoine et al., 2007) |

