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"El saber de mis hijos hará mi grandeza"

Computational fluid dynamics as a technique for the UV-C light dose determination in horticultural products

Dinámica de fluidos computacional como técnica para la determinación de la dosis de luz UV-C en productos hortofruticolas

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ABSTRACT

Horticultural products disinfection with short wave ultraviolet light (UV-C) depends mainly on dose. This parameter is defined as the product between time and intensity radiation. In general, short doses cause beneficial or hormetic effects, such as decrease of microbial load and fruits and vegetables quality preservation. While UV-C light high doses or long exposure times generate changes in those products, such as enzymatic browning, loss of texture, among others, which cause a decrease in shelf life and functional properties. Therefore, this article presents the most cited techniques to determine doses in horticultural products, some experimental and others that employ microbiology and mathematical knowledge, radiochromic films and computational fluid dynamics (CFD). The review highlights that CFD allow the development of simulations in real environments, quickly and economically, including radiation models prone to experimental validation and help to improve the arrangement of horticultural products in the equipment to achieve a uniform irradiation.

Keywords: Safety, hormesis, UV-C radiation, simulation, mathematical modeling.

RESUMEN

La desinfección de productos hortofrutícolas con luz ultravioleta de onda corta (UV-C) depende principalmente de la dosis. Este parámetro se define como el producto entre el tiempo e intensidad de radiación. En general, las dosis cortas ocasionan efectos benéficos u horméticos, tales como la disminución de carga microbiana y preservación de la calidad de las frutas y hortalizas durante su vida útil. Mientras que las dosis altas o los largos tiempos de exposición a la luz UV-C generan cambios en dichos productos, tales como el oscurecimiento enzimático, pérdida de textura, entre otros, los cuales provocan una disminución de la vida útil y la pérdida de las propiedades funcionales. Por lo tanto, este artículo presenta las técnicas más citadas para determinar las dosis en productos hortofrutícolas, algunas de carácter experimental y otras que emplean conocimientos de microbiología y matemáticas, películas radiocrómicas y la dinámica de fluidos computacional (CFD). La revisión destaca que la CFD permite el desarrollo de simulaciones en entornos reales de forma rápida y económica, comprende modelos de radiación que pueden ser validados de forma experimental y ayuda a mejorar la disposición de los productos hortofrutícolas en el equipo para lograr una irradiación más uniforme.

Palabras clave: Inocuidad, hormesis, radiación UV-C, simulación, modelamiento matemático.

INTRODUCTION

Horticultural products are highly perishable and can become contaminated with microorganisms that cause rot, or pathogens at any point of the agro-industrial chain, whether in production, harvest, post-harvest, processing, storage, distribution, sale and final consumption (Harris *et al.*, 2011). Therefore, it is important to assure that the intake of these products does not cause harm to consumers. One of the main postharvest operations that takes place is surface disinfection. For this, some polluting and toxic human health chemical compounds are usually used (Pinela and Ferreira, 2017). Accordingly, the UV-C light application has been investigated and implemented, which is considered a non-ionizing radiation emitted by mercury lamps in wavelengths from 100 to 280 nm (Shama, 2005), and acts as a germicide or mutagenic (Terry and Joyce, 2004).

For UV-C light application, there are some critical factors, such as the material to irradiate, the operating conditions and the microorganisms involved. As the process depends on the shape, nature, water activity and composition of the matrix to irradiate, several reports coincide in that a greater microbial inactivation efficiency is achieved in fruits with smooth and flat surfaces. The germicidal effect varies,

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essentially, depending on DNA composition of microorganisms, so it is recommended to achieve a wavelength close to the DNA absorption peak (260-265 nm) (Millán-Villarroel *et al.,* 2015). On the other hand, each fruit and vegetable have different capacity to resist the treatment, so it is necessary to find an adequate distance between the source of radiation and the product to irradiate, as well as the optimal dosage application, to guarantee safety and avoid loss of quality (Stevens *et al.*, 1997; Quintero-Cerón *et al.*, 2013). Taking into account the above, this review aims to highlight the dose value during UV-C light treatments and describe the most cited techniques to determine this parameter, deepening the use of computational fluid dynamics (CFD).

UV-C light application in food agro-industry

UV-C light was initially incorporated into devices designed for disinfected or sterilized food that had to pass through a station where filling and aseptic packaging were carried out (Bachmann, 1978; Bachmann and Sturm, 1979). Subsequently, the study of its application in preformed boxes to eliminate microorganisms such as *Bacillus subtilis* and its vegetative forms was continued (Stannard *et al.*, 1983; 1985). However, it was only until the nineties that the positive effects of UV-C application in horticultural products were observed (Stevens *et al.*, 1990), hormesis was referred for the first time (Liu *et al.*, 1993) and fruit disinfection equipments for continuous production lines were manufactured (Wilson *et al.*, 1997). Finally, in the 21st century, the effectiveness of short doses of UV-C light was investigated to obtain responses in exotic and fresh-cut fruits (Gutiérrez *et al.*, 2016; Huang *et al.*, 2017) (Figure 1).

Beneficial and adverse effects of UV-C light application in fruit and vegetable products

UV-C light treatments in fruits and vegetables are determined considering the dose, namely, the amount of energy applied during a time interval (Shama, 2007). In some investigations, short irradiation times led to hormonal effects

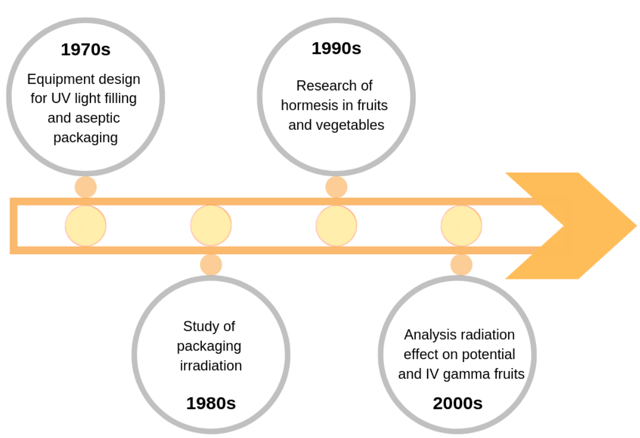

Figure 1. Timeline of UV-C light application in food agro-industry.
Figura 1. Línea de tiempo de la aplicación de luz UV-C en la agroindustria alimentaria.

development and microbial load reduction, while high doses or continuous exposure generated quality loss, as well as a decrease in shelf life and antimicrobial activity (Rivera-Pastrana *et al.*, 2007; Quintero-Cerón *et al.*, 2013).

Several reports indicate that UV-C low doses application involves some benefits to irradiated products (Figure 2a). A dose of 1.18×10^3 mW-s/cm^2 caused ascorbate peroxidase accumulation and lower lipase activity in fresh cut melon, which meant a decrease in rancidity and greater firmness during shelf life (Lamikanra *et al.*, 2006). In addition, the use of low doses did not affect bioactive compounds such as phenols, flavonoids, antioxidants and pigments in blueberries (Wang *et al.*, 2009), strawberry 'Diamond' (Beltrán *et al.*, 2010), mandarin 'Satsuma' (Shen *et al.*, 2013), garlic 'Danyang' (Park and Kim, 2015) and purple cabbage (Wu *et al.*, 2017). In mango 'Tommy Atkins', UV-C light had an impact on fenilpropanoid metabolism, increasing phenylalanine ammonia-lyase (PAL) activity, which resulted in appearance and texture preservation, decrease rot symptoms, and an increase of antioxidant capacity, phenolic compounds content and flavonoids during cold storage (González-Aguilar *et al.*, 2001; 2007). Table 1 shows other benefits determined by UV-C light different doses application in horticultural products, such as tomato, mangosteen, and apricot, among others.

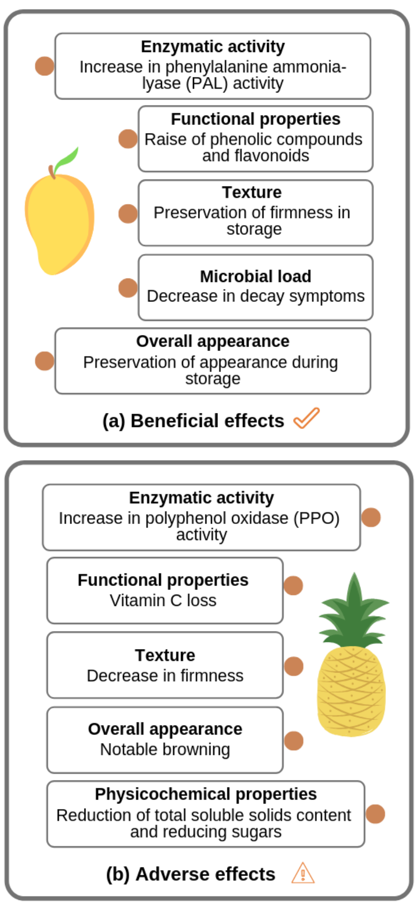

Figure 2. Beneficial (a) and adverse (b) effects of UV-C light application in horticultural products.
Figura 2. Efectos benéficos (a) y adversos (b) de la aplicación de luz UV-C en productos hortofrutícolas.

Table 1. Recent studies of UV-C light application in horticultural products.
Tabla 1. Estudios recientes de la aplicación de luz UV-C en productos hortofrutícolas.

Horticultural product	Dose	Benefits	Authors
Tomato (*Solanum lycopersicum*)	To reach total dose (4 kJ/m^2) the fruit was rotated and two sides were irradiated, each for 6 min.	The expression of genes encoding key enzymes in phenylpropanoid pathway was induced. Increase in total and individual phenolic compounds content.	Liu *et al.* (2018)
Mangosteen (*Garcinia mangostana* L.)	Fruits were placed 15 cm from the UV-C light source and rotated to asssure uniform exposure. The doses were 6, 13, 26 and 40 kJ/m^2.	A treatment with a dose of 13 kJ/m^2 generated the greatest decay reduction. Increase in phenylalanine ammonia-lyase (PAL), chitinase, β-1, 3-glucanase and peroxidase (POD) enzymes activity. Decrease in weight loss and respiratory rate during storage.	Sripong *et al.* (2019)
Fresh-cut lotus root (*Nelumbo nucifera* Gaertn.)	Plant material was packed in bags and disposed at 30 cm from a germicidal lamp. The doses within packages were 0.3, 1.5, 3, 6, 12 kJ/m^2.	The doses of 1.5 and 3 kJ/m^2 caused a decrease in soluble quinones and malondialdehyde content, and in polyphenol oxidase (PPO), peroxidase (POD) and phenylalanine ammonia-lyase (PAL) enzymes activity. Treatments with doses of 1.5-12 kJ/m^2 inhibited microbial growth.	Wang *et al.* (2019)
Albaricoque (*Prunus armeniaca* L.)	7.75, 11.63, 15.50, 19.38, 23.26, 31.01, 34.88, 38.76 and 48.45 kJ/m^2.	The dose of 31.01 kJ/m^2 caused a 3-log reduction in the number of total mesophilic aerobic bacteria. A 2.38-log reduction was achieved for yeast and mould count with a dose of 7.75 kJ/m^2. All the treatments generated complete inactivation of coliform bacteria.	Taze and Unluturk (2018)
Tahitian lime (*Citrus latifolia*)	Fruits were located 20 cm from UV-C light source. The doses were 3.4, 7.2 and 10.5 kJ/m^2.	A dose of 10.5 kJ/m^2 reduced ethylene production, weight loss and respiration rate during storage. It also allowed the retention of calyx and peel green colour.	Pristijono *et al.* (2019)

Regarding adverse effects (Figure 2b), evidence exist indicating that a high dose (10 kJ/m^2) triggered pheophytin formation in broccoli, similarly to non-irradiated vegetables (Costa *et al.*, 2006). Likewise, the exposure of apple 'Granny Smith' slices to 5.6 kJ/m^2, 8.4 kJ/m^2 and 14.1 kJ/m^2, caused a decrease in shelf life due to enzymatic browning (Gómez *et al.*, 2010). Irradiation of transversely cut pineapple trunks, with doses of 4.5 kJ/m^2 per side for 60 and 90 s, resulted in enzymatic browning and vitamin C content decrease during storage period (Pan and Zu, 2012). Imaizumi *et al.* (2018) found that after exposure of persimmon and cucumber to a radiation intensity of 12.9 W/m^2 for up to 15 min, no increase was evident in phytonutrients levels, such as polyphenols, β-carotene, ascorbic acid and chlorophyll. On the contrary, some fruits got darked during storage, due to tannins transfer from parenchyma to epidermal tissue, while cucumber exocarp luminosity was affected, since cuticle was damaged by irradiation and there was a slight loss of moisture.

Techniques for horticultural products UV-C light dose determination

Optimal UV-C light dose determination in horticultural products usually takes into account previous investigations. The literature does not report many techniques used for this purpose, nor their classification due to their nature. However, they can be identified according to principles and elements adapted. It is possible to find some of empirical or experimental nature, others that include microbiology and mathematics, materials with significant physical properties and, finally, computer science and energy transport equations, like CFD and others (Figure 3).

Experimental techniques

The trial and error principle governs experimental techniques. For their development, researchers test different combinations of time and radiation intensity in different equipment configurations, or UV-C light sources and evaluating horticultural products orientation to achieve uniform irradiation. Previous reports indicate that the use of some doses proves to be beneficial (Liu *et al.*, 2018). Baka *et al.* (1999) applied doses of 0.25 and 1 kJ/m^2 to strawberries, and between 1.3 and 40 kJ/m^2 in tomatoes (Liu *et al.,* 1993); to ensure a homogeneous irradiation, the design included four sub-doses applied at different positions. Treatments in strawberries generated a shelf life increase and reduced decay caused by *Botrytis cinerea* at storage temperatures of 4 and

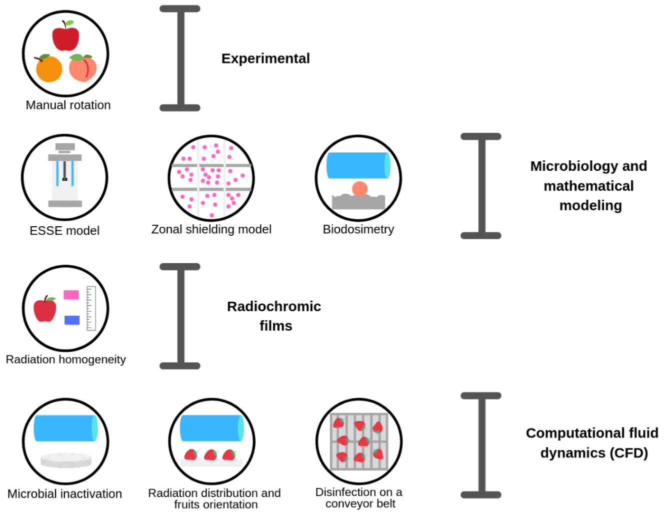

Figure 3. Methods for the UV-C light optimal dose determination in horticultural products.
Figura 3. Métodos para la determinación de la dosis óptima de luz UV-C en productos hortofrutícolas.

13 °C. While in tomato, the dose allowed rot control caused by molds of *Alternaria alternata*, *Botrytis cinerea* and *Rhizopus stolonifer*, and produced a delay in maturation. On the other hand, grapes were exposed to doses ranging from 0.125 to 4 kJ/m^2, but only by two sides. Doses greater than 0.5 kJ/m^2 caused an induced resistance to gray mold (*Botrytis cinerea*) (Nigro *et al.*, 1998). Another research compared apples, tangerines and peaches irradiation with 7.5 kJ/m^2, 1.3 kJ/m^2 and 7.5 kJ/m^2, respectively, and dose distribution effect, on four, two and one side, as well as a stem-end stationary treatment. The latter procedure caused a rot resistance in the mentioned horticultural products, even better than when they were rotated the greater number of times. This may be due to penetration of radiation into the outer layers of dermal tissues at stem end of each fruit, where UV-C light is in contact with a photoreception site, or because of a signal transmitted systematically from stem end to vascular tissue floem (Stevens *et al.*, 2005).

Microbiological techniques with mathematical models

These techniques emerged mainly to establish whether mathematical modeling of microorganisms inactivation on solid objects surfaces could contribute to UV-C light commercially disinfection development (Gardner and Shama, 1998). Thus, it is possible to obtain both theoretically and experimentally response of nonpathogenic spores behavior to radiation, by evaluating their fractional survival to conditions in which aims to estimate doses (Obande and Shama, 2011). According to Alfano *et al.* (1986), there are two main types of radiation models for this case: incidence and emission models. Incidence models requiere the energy distribution adjacent to the system, developed in two or three dimensions, and also subdivided in radial incidence model (RI), partially diffuse incidence model (PDI) and diffuse incidence model (DI). These models are not recommended for equipment design since they always need experimentally adjustable parameters. On the other hand, the basis of emission models reside on the characteristics of emission source. They are classified in line source models (LS) and extense source models (ES), which considere the lamp as a line source and as a perfect cylinder with different ways of emission, respectively. One of the initial studies carried out by Gardner and Shama (1999), consisted of a bioassay with *Bacillus subtilis* spores. These were deposited on filter paper cylinders surface (cylinder 1: diameter 66 mm, length 20 mm; cylinders 2 and 3: diameter 40 mm, length 75 mm) suspended in a UV-C field created by four mercury lamps located in the upper part of a disinfection chamber composed of a glass column of 0.23 m diameter and 1 m length. The radiation intensities were experimentally found on the cylinder base and laterals, corelating the microorganisms survival with dose applied by means of a curve; they were also predicted with a spherical emission model (ESSE), assuming volume of radiation source comprised elements of differential volume. In short, different work obtained a good agreement (in a range of 75 to 95%) between predicted and experimental values, and a considerable variation observed between the upper part of the cylinder, which received a uniform irradiation, and laterals.

Afterwards, Gardner and Shama (2000) used the previously described information to model the light incidence on the inactivation of microorganisms, delimiting the number of zones where distribution of microorganisms was analyzed by means of nonlinear programming and the population fraction before and after UV-C light application. Thus, inactivation data were required for the conditions in which microorganisms were completely exposed to radiation, as well as microbial kinetics found during treatment. This provide quantitative information of necessary doses for specific reductions of microbial load.

To simulate and evaluate dose delivered distributions in spherical fruits during UV-C light treatment, biodosimetry was applied in polystyrene spheres of 70 mm diameter which included membranes impregnated with *Bacillus subtilis* spores in five angles (0, 45, 90, 135 and 180 degrees). Dose delivered determination was approached theoretically and experimentally for spheres irradiated in different positions and in a rotating device for up to 80 s. Therefore, a theoretical dose of 10.6 J was calculated by means of the inverse square law, and doses of 9.1, 10.7 and 6.1 J were estimated for when the spheres were rotated one, two and four times, respectively, adapting the surviving spores fraction to a dose-response curve. For exposure during an 80 s continuous mechanical rotation, 3.5 J were achieved, namely, only 33% of theoretical dose. Upon doubling exposure time, 10.2 J were irradiated. Likewise, the when evaluating the effect of interference from adjacent spheres, it resulted in the inactivation of spores along the rotation axis upon reaching a dose of 8.9 J, a smaller amount compared to the case of a sphere (Obande and Shama, 2011).

Radiochromic films

Radiochromic films are composed of plastic materials such as polysulfone, diazo and polyvinyl chloride, to which a dye and a releasing agent are added for use in UV-C radiation actinometry. They are sensitive indicators and the changes in their properties after treatments can be measurable (Abdel-Fattah *et al.*, 2000). Commonly, the response of films is expressed in terms of their optical density change, which refers to optical density difference of a piece of film before and after irradiation (Devic, 2011). Several reports state that radiochromic films have been useful in medical radiation and solar radiation dosimetry (Butson *et al.*, 2003; 2010).

Yan *et al.* (2017) used radiochromic films in apples Fuji with the aim of knowing what kind of film and wavelength to use to calculate UV-C light doses. Hence, it was noted that FWT film (43.5 µm in thickness, 10 × 10 mm in size) was the most sensitive to UV-C radiation between the ranges of 0 to 12 kJ/m^2 compared to B3WINDOSE film (19.4 µm in thickness, 10 × 10 mm in size), which was measured by optical density at 510 and 600 nm in a radiochromic reader. As a result, UV-C radiation dose was expressed with a polynomial equation in terms of A510 nm. In addition, to achieve a uniformity of dose in apples, trays of reflective materials were evaluated at 5 cm below fruits, including a black cloth, aluminum foil and a stainless steel, as well as a rotating device. With this last element, greater homogeneity was achieved in the irradiation, although fruits did not receive doses as significant as with reflective materials.

Computational fluid dynamics (CFD)

Computational fluid dynamics (CFD) is a numerical technique developed with computers. It allows the solution or quantitative prediction of a fluid flow phenomena based on the laws of conservation of mass, momentum and energy, under conditions defined in terms of flow geometry, physical properties of fluid, and boundary and initial conditions of a flow field (Scott and Richardson, 1997; Hu, 2012). The CFD main advantages are the generation of detailed and complete information of all the relevant variables in an economical and fast way, ease in the modification of parameters, optimization of designs, simulation in realistic and ideal conditions, and investigation of undesired situations (Hu, 2012). The links between CFD and the processes associated with agri-food industry are deep, since they are used regularly to efficiently improve the quality, safety and shelf life of food products (Norton and Sun, 2007). This has been evidenced by the development of multiple researches focused on unit operations such as drying, pasteurization, sterilization, humidification, refrigeration, mixing and baking (Xia and Sun, 2002; Ren and Zhang, 2011; Kaushal and Sharma, 2011).

Koutchma *et al.* (2009) reported that CFD methods are useful for finding UV-C light dose distributions, but it is necessary to consider models that can be validated with experimental data (Sandia National Laboratories, 2007). The radiative energy balance is the radiative transfer equation (RTE) which describes radiative intensity field as function of location, direction and spectral variable (wavelength). The intregration of RTE leads to a conservation of radiative energy statement applied to an infinitesimal volume (Modest, 2013). The different methods to work out RTE include P-1, Rosseland, surface-to-surface, discrete ordinates and discrete transfer radiation models (ANSYS Inc., 2009). The discrete ordinate (DO) method is one of the most commonly applied to solve the radiative transfer equation for a finite number of discrete solid angles, each associated with a vector direction in cartesian system (Bartzanas *et al.*, 2013; He *et al.*, 2018). Besides, DO model is expressed as a function of absorption, scattering, reflection and emission, and considers non-gray radiation, semitransparent, specular and diffuse media (ANSYS Inc., 2009, Trivittayasil *et al.*, 2016). Previously, this model has been used in different studies related to wastewater disinfection with UV reactors (Hashemabadi *et al.*, 2014; Sultan, 2016).

Trivittayasil *et al.* (2015) described UV-C light *in vitro* inactivation of *Cladosporium cladosporioides* and *Penicillium digitatum*, responsible for strawberries decay. The experimentation was carried out with potato dextrose agar (PDA) plates that individually contained 10^7 CFU/mL of microorganisms under study. Those plates were placed at different distances from a germicidal lamp (50, 100, 150 and 200 mm) and irradiated with an average radiation intensity of 100 W/m^2 for up to 30 min. ANSYS Fluent 13.0 software and DO radiation model were employed to find the average irradiation intensity on the upper surfece of the agar at mentioned distances, since it was a necessary parameter in calculation of microbial kinetics and prediction models based on UV-C dose. This study estimated that treatments caused microbial population to decrease up to four logarithmic units and that the average irradiation intensity on the upper surace of the agar varied from 13.8 to 2.13 W/m^2 and from 13.2 to 2.29 W/m^2 for the plates with the suspensions of *C. cladosporioides* and *P. digitatum*, respectively. It was also found that the survival curve of *C. cladosporioides* was biphasic in nature, which meant that the inactivation rate was high at the beginning and decreased when dose was increase, while the survival of *P. digitatum* was adjusted to a first order kinetic.

Subsequently, Trivittayasil *et al.* (2016) developed simulations using ANSYS Fluent 14.0 software using and DO radiation model (Figure 4), in order to determine the most suitable orientation for strawberry irradiation with a single UV-C light germicidal lamp. The fruit was placed in three orientations with calyx on its side, top, and bottom. The area not directly exposed to radiation (radiation intensity lower than 0.5 W/m^2) corresponded to 43.9, 55.7 and 51.9 % of total area, respectively. The maximum intensity received by the strawberry with calyx on its side, top and bottom were 5.13, 6.06 and 5.86 W/m^2, respectively. Therefore, it was determined that with side calyx on its side, the largest strawberry area was irradiated at a lower radiation intensity compared to other orientations. Likewise, the research analyzed the effect of the number of lamps (2, 4 and 8) and their positions to get a uniform radiation for nine strawberries arranged with calyx

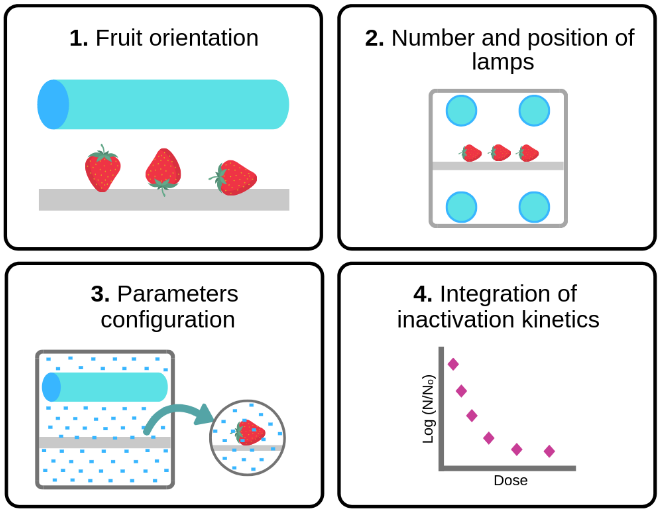

Figure 4. Steps for CFD simulation of strawberry disinfection.
Figura 4. Pasos para la simulación de la desinfección de fresas mediante CFD.

on their side in a linear low-density polyethylene (LLDPE) film tray. Thus, the best distribution of UV-C light dose was obtained with the model of four lamps organized in such a way that two were both on the top and bottom of fruits and at a horizontal distance between them of 300 mm, reaching a minimum and maximum intensity of 0.071 and 4.35 W/m^2, respectively. Finally, the integration of inactivation models of *C. cladosporioides* and *P. digitatum* reported in the study developed by Trivittayasil *et al.* (2015), with radiation transfer model for this configuration, showed that the times required for the inactivation of one logarithmic unit of *C. cladosporioides* and *P. digitatum* were 226 s and 96 s, respectively.

Additionally, to detail UV-C light doses distribution during strawberries disinfection in a conveyor system, with a speed control device by means of a three-dimensional irradiation model based on a DO model and a sliding mesh method, different strategies are studied. For instance, Tanaka *et al.* (2016) simulated in ANSYS Fluent 14.0 software four models, which consisted of configuration of four different sizes germicidal lamps (90 or 250 mm with a 15 mm diameter, or 985 mm with a 22.5 mm diameter), installed in parallel or vertical to movement direction, and nine strawberries placed on a UV-C-transparent linear low density polyethylene (LLDPE) film tray of 1 mm thickness. In such a way, that they determined the total UV-C dose distribution to accumulate UV-C incidents of two doses on strawberries surface during six positions dependent of time. The results showed that models with four lamps installed in parallel to movement direction provided a dose uniform distribution, and that to achieve the inactivation of three logarithmic cycles of *P. digitatum* on strawberries surface, it was necessary a UV-C light treatment of 131 s.

As for the simulations, it is essential to have a computer-aided design (CAD), as well as to define a set of boundary conditions and some important parameters. Mainly, absorption coefficient, refractive index and density of participationg medium (air) and the tray that contains horticultural products, UV power emitted by lamp, equipment average radiation intensity and surfaces emissivity and diffuse fraction (Trivittayasil *et al.*, 2016) (Figure 5). Consequently, tray refractive index is estimated at peak wavelength in which lamp emits UV-C radiation (253.7 nm), while absorption coefficient is calculated by transmittance, namely, evaluating how radiation intensity is reduced through tray (Ho, 2008). Lamp UV power is an information given by manufacturer and intensity radiation is measured with a radiometer or UV-meter; although both parameters can be calculated by

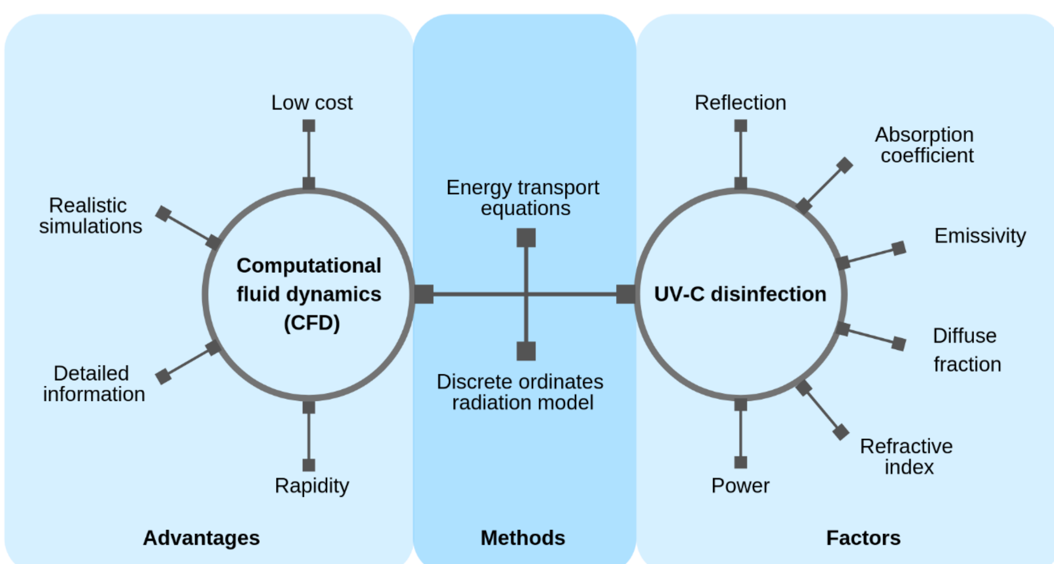

Figure 5. Computational fluid dynamics (CFD) advantages, methods and factors to simulate UV-C light horticultural products disinfection.
Figura 5. Ventaja, métodos y factores de la dinámica de fluidos computacional (CFD) para simular la desinfección de productos hortofrutícolas con luz UV-C.

Lambert law or mathematical models derived from it (Chang *et al.,* 1985; Gardner and Shama, 1999). Moreover, lamp surface can be estimated as semitransparent with a diffuse fraction of one and emissivity of 0.89, since it is the radiation source (Trivittayasil *et al.,* 2015, 2016). According to Tanaka *et al.* (2007), the other surfaces including those of horticultural products have been designated as opaque with emissivity and diffuse fraction of 0.95 and 0.5, respectively, in order to all absorbed radiation power is dissipated at the surface. Figure 6 illustrates a CFD simulation of a UV-C light disinfection process, and it is emphasized that radiation distribution also depends on horticultural products shape.

CONCLUSIONS

The analyzed literature review allowed knowing that UV-C light dose is a relevant parameter in the application of this technology to maintain quality and safety of horticultural products. The determination of this parameter has been carried out using different techniques that have generally focused on the reduction of microorganisms that cause postharvest rot and some were developed with equipment that is difficult to acquire or manufacture. However, CFD stands out because simulations are done quickly in a computer, including a real environment, which the properties of the elements of system geometry are taken and validatable experimental models can be integrated with any type of microorganism kinetics inactivation. In addition, the use of materials, reagents and time of experimentation are reduced, and it is possible to create and test new configurations with equipment and horticultural products to improve disinfection at the pilot and industrial level.

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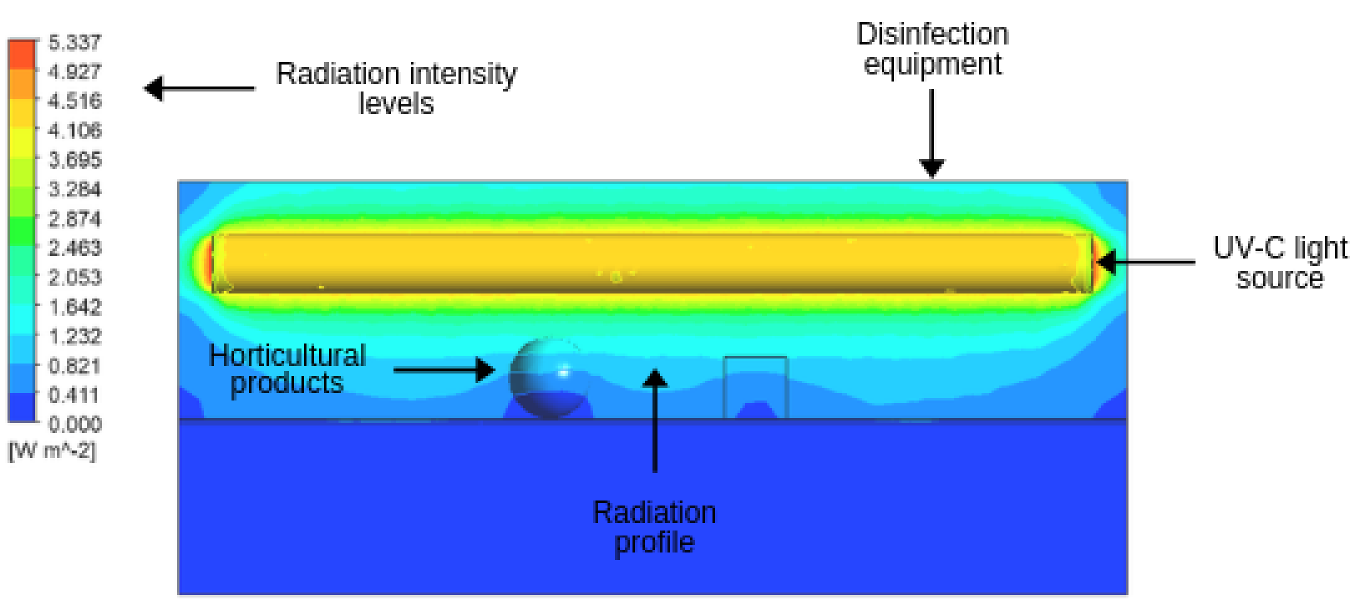

Figure 6. CFD simulation of horticultural products disinfection.
Figura 6. Simulación de la desinfección en CFD de productos hortofruticolas.

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