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CFD Analysis of UV-C Intensity Radiation Distribution and Inactivation of Foodborne Pathogens on Whole and Minimally Processed Mango

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Abstract: Ultraviolet shortwave (UV-C) is a technology for postharvest fruit disinfection. This study aimed to use computational fluid dynamics (CFD) based on the discrete ordinate (DO) radiation model to analyze the distribution of UV-C intensity on whole and minimally processed mangoes within a disinfection chamber and to predict treatments against foodborne pathogens. The mango spears were oriented both parallel and perpendicular to the lamp and positioned at varying distances from the radiation source (50, 75, and 100 mm for spears and 100 mm for whole fruit). CFD simulations integrated with *in vitro* kinetic parameters enabled predictions of the time and doses needed to inactivate one to three logarithmic units of pathogens on the fruit surface. The highest average radiation intensity values were recorded for the whole mango oriented parallel to the lamp at 100 mm and the spears oriented normally to the lamp at 50 mm. The estimated times to achieve inactivation of one to three logarithmic units of microorganisms ranged from approximately 15 to 6540 s, while the doses necessary for this inactivation were, on average, 1.854, 5.291, and 10.656 kJ/m^2, respectively. CFD simulations are valuable for optimizing UV-C treatments in large-scale designing from both microbicide and sustainable perspectives.

Keywords: disinfection; irradiation; computational fluid dynamics; DO model; inactivation; modeling

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1. Introduction

Mango is a fruit of significant nutritional value and a source of dietary antioxidants, including ascorbic acid, carotenoids, and phenolic compounds [1]. However, the presence of foodborne pathogens in this fruit has been observed even at low temperatures. This is because mango is considered a favorable substrate due to its low acidity, providing conditions that allow microorganisms to survive and multiply [2]. In mangoes, the primary microorganisms linked to foodborne diseases include *Salmonella*, *Escherichia coli*, *Listeria monocytogenes*, and *Shigella flexneri* [3–5]. Foods contaminated with these microorganisms can cause symptoms like fever, headache, diarrhea, and muscle aches in non-invasive cases. However, in more severe invasive forms, they may lead to conditions such as abortions, septicemia, meningitis, and encephalitis, with a high mortality rate of 20–30% [6]. Therefore, it is crucial to implement measures like surface disinfection during postharvest to prevent the growth of pathogens.

Chlorinated compounds are commonly used to disinfect fruits and vegetables after harvest because they are cost-effective and highly effective against a wide range of microorganisms. However, a significant drawback is that the continuous addition of chlorine to water can lead to the formation of carcinogenic substances, posing risks to both human and environmental health [7]. As a result, alternative methods, such as shortwave ultraviolet (UV-C) light treatments, have been suggested. UV-C is a type of non-ionizing radiation with wavelengths ranging from 100 to 280 nm. It has a microbicidal effect by causing mutations in the DNA of microorganisms [8]. Similarly, UV-C can enhance the defense mechanisms in plant tissues by promoting the accumulation of phenylpropanoids, delaying senescence, preserving quality, and extending the shelf life of fruits and vegetables [9].

The effectiveness of UV-C treatment depends on both the distance of the vegetable material from the lamp and the radiation dose applied [10]. The dose refers to the amount of energy delivered, measured as radiation intensity over a specific time [8]. In this context, radiation intensity represents the rate at which radiant energy impacts a surface from various directions [11]. Typically, this parameter is calculated by averaging the readings of incident radiation at multiple points within the disinfection equipment to ensure uniform exposure of the product to radiation [12]. In a preceding report, Yan et al. [13] inoculated peaches cv. PF25 with a five-strain cocktail of *E. coli* O157: H7 and treated the fruit with UV-C doses ranging from 0 to 442 mJ/cm^2. The peaches were then stored for 7 days at 20 °C. A UV-C dose of 442 mJ/cm^2 led to a reduction in the *E. coli* population by 1.4 log CFU per fruit. In a separate study, Mukhopadhyay et al. [14] demonstrated that UV-C doses between 0.60 and 6 kJ/m^2 resulted in a 2.3 to 3.5 log CFU per fruit reduction in *E. coli* and a 2.15 to 3.1 log CFU per fruit reduction in *Salmonella* on grape tomatoes. However, there are limited studies exploring the UV-C effect on contaminated fruit with foodborne pathogens, particularly *Listeria monocytogenes*.

One numerical simulation tool that can be used to analyze radiation models for evaluating radiation intensity distribution and dosage during the UV-C disinfection process is computational fluid dynamics (CFD) [15]. CFD enables the description of fluid flow through equations based on the principles of mass, momentum, and energy conservation [16]. Previous studies have demonstrated the utility of the discrete ordinate (DO) radiation model in simulating the inactivation of molds such as *Cladosporium cladosporioides* and *Penicillium digitatum*, which contribute to postharvest fruit rot [17]. It has also been effective in modeling UV-C radiation intensity distribution and mold inactivation on strawberries [18], as well as UV-C dose distribution and mold inactivation for strawberries placed on a conveyor belt [19]. Garzón-García et al. [20] utilized CFD to model the UV-C survival of foodborne pathogens (*Escherichia coli* O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes*) and to predict microbial inactivation in 'Tommy Atkins' minimally processed mango. They found that integrating CFD simulations with kinetic parameters allowed for the estimation of UV-C doses around 6 kJ/m^2 for treating mango spears inoculated with these microorganisms. However, this study was conducted from a single position and at a fixed distance between the mango spears and the UV-C source. Thus, the objective of this research was to analyze the UV-C radiation intensity distribution on whole and minimally processed 'Tommy Atkins' mangoes at various positions and locations within a cost-effective disinfection chamber. Additionally, it aimed to predict the times and doses of UV-C treatment needed to achieve one to three logarithm units of inactivation of *E. coli* O157, *S.* Typhimurium, and *L. monocytogenes* on the surface of the fruit.

2. Materials and Methods

2.1. Experimental Unit Configuration

A disinfection chamber, developed and tested as a prototype for food safety and preservation research at Universidad de Sonora, was considered. The chamber dimensions are 200 mm in height, 460 mm in length, and 190 mm in width. Inside the equipment, the radiation source was positioned 146 mm above the base and consisted of a Lumiaction G15T8 germicidal lamp (28 mm in diameter and 451 mm in length; Lumiaction Co., Taipei, Taiwan) with a nominal power of 15 W, producing 3 W of UV-C radiation.

2.2. Radiation Model

According to Zhao and Liu [21], the Radiative Transfer Equation (RTE) is a fundamental equation governing the propagation of radiation, which enables the analysis of radiative transfer in gases, semitransparent liquids, and solids. The discrete ordinate (DO) radiation model, on the other hand, is a method used to solve the RTE within a discretized solid angle domain, calculating radiation intensity based on absorption, scattering, reflection, and emission (Equation (1)) [18].

$$\nabla.\left(I\left(\vec{r},\vec{s}\right)\vec{s}\right) + (\alpha + \sigma_s)I\left(\vec{r},\vec{s}\right) = \alpha\eta^2\left(\sigma T^4/\pi\right) + (\sigma_s/4\pi)\int_0^{4\pi} I\left(\vec{r},\vec{s}'\right)\Phi\left(\vec{s},\vec{s}'\right)d\Omega' \quad (1)$$

where the radiation intensity (I) is dependent on the position (r) and distance (s). α denotes the scattering direction vector; η is the refractive index; σ refers to Stefan–Boltzmann constant; σ_s is the scattering coefficient; T corresponds to the local temperature; Φ represents the phase function, and Ω is the solid angle. Previously, Garzón-García et al. [20] validated the DO model for the disinfection chamber using vertical and horizontal measurements by means of simulations and a UV meter.

2.3. Geometry and Meshing

The geometries considered for this study were created using Design Modeler (Academic Student version 2020 R1, ANSYS Inc., San Jose, CA, USA). For the analysis of UV-C disinfection of minimally processed mango, six geometries were designed, which included eight mango spears, each measuring 20 mm in height, 60 mm in length, and 20 mm in width. The fruit pieces were positioned either parallel (PS) or perpendicular (NS) to the lamp. The PS pieces were placed on four aluminum square bars, each with a 12.7 mm diameter, while the NS pieces were positioned on two bars of the same size. The bars were located 59 mm from the edges of the equipment's smaller sidewalls. The PS pieces were arranged in two rows, with each row positioned 28.7 mm from the center of the equipment and each row containing four pieces spaced 34 mm apart (Figure 1a). The NS pieces were aligned in a single row in the center of the equipment, with a spacing of 26 mm between them (Figure 1b). The distances between the bars and the radiation source were set at 50, 75, and 100 mm.

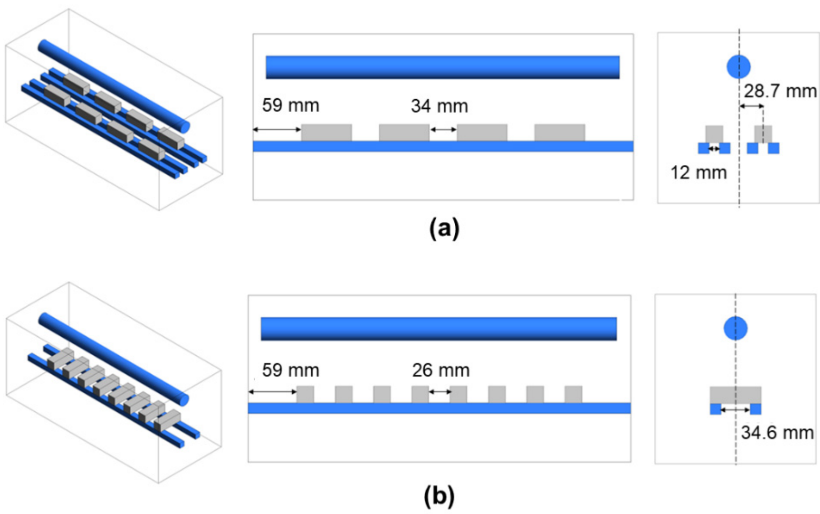

Figure 1. Isometric, horizontal, and vertical projection of mango spears positioned parallel (**a**) and perpendicular (**b**) to the lamp.

For the whole fruit, two geometries were designed, one of which included a mango cv. 'Tommy Atkins' with real dimensions (90 mm in height, 130 mm in length, and 90 mm in diameter) obtained through 3D scanning. The fruit was positioned both parallel (PW) (Figure 2a) and normal (NW) (Figure 2b) to the lamp using two 12.7 mm square aluminum bars. The PW and NW configurations were placed approximately 165 mm and 185 mm from the smaller sidewalls of the disinfection chamber, respectively. The distance between the square bars and the lamp was 100 mm.

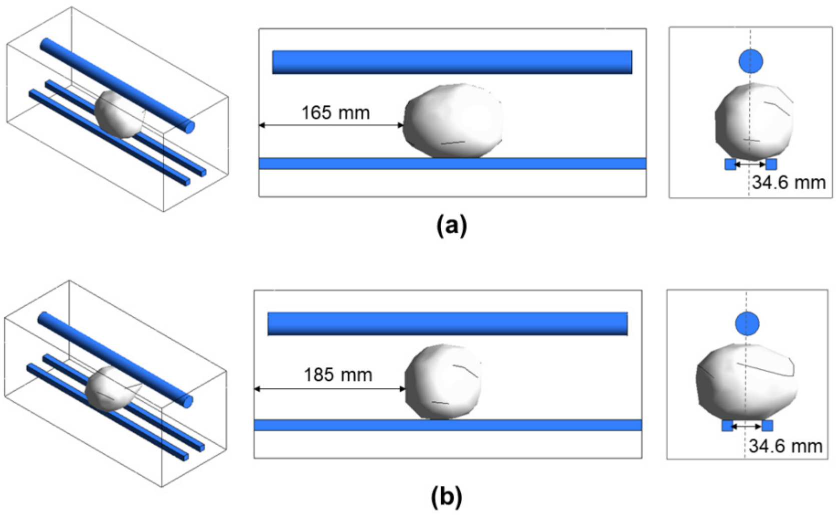

Figure 2. Isometric, horizontal, and vertical projection of whole mango positioned parallel (**a**) and perpendicular (**b**).

The mesh for both the equipment and mango geometries was generated using Meshing (Academic Student version 2019 R3, ANSYS Inc., San Jose, CA, USA) with the automatic meshing method (Figure 3). The quality of the mesh was set as high. Tetrahedral discretization was applied to all the disinfection chamber walls, and face meshing was used on the larger walls. The number of mesh elements ranged from 136,868 to 143,868 for the whole mango and from 131,002 to 172,938 for the minimally processed mango.

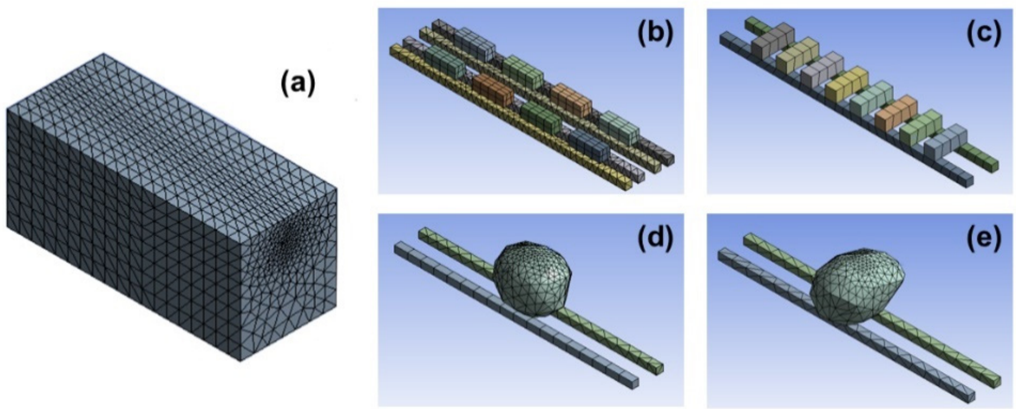

Figure 3. The mesh, including the equipment without any accessories (**a**); mango spears positioned parallel (**b**) and perpendicular (**c**) to the lamp, as well as the whole mango positioned parallel (**d**) and perpendicular (**e**) to the lamp.

2.4. Computational Domain and Boundary Conditions

According to Garzon-García et al. [20], the DO radiation model was employed to solve the RTE considering a solid angle discretization with theta and phi divisions of 10×10 and theta and phi resolutions of 3×3. The continuity, momentum, and energy equations for incompressible laminar flow were solved for the geometries of the system. For the boundary conditions, data entered Fluent (Academic Student Version 2019 R3, ANSYS Inc., San Jose, CA, USA) are summarized in Table 1. The radiation intensity on the lamp tube was assumed to be diffuse radiation. The volumes inside the lamp and mango were left empty. All walls were treated as opaque, except for the lamp walls, which had a diffuse fraction of 1, while the other walls had a diffuse fraction of 0.5 [18].

Table 1. Parameters of boundary conditions and computational domain for simulations.

Parameter	Value
Air density (kg/m^3) [1]	1.225
Aluminum density (kg/m^3) [1]	1190
Emissivity of the walls of the equipment, bars of aluminum, and mango [1]	0.95
Emissivity of the lamp wall [1]	0.89
Average radiation intensity in the lamp tube (W/m^2) [2]	30.5

[1] Garzón-García et al. [20]. [2] Measurement.

2.5. Solution Setup

The steady-state governing equation was solved using the SIMPLE algorithm, with the first-order method applied to the DO radiation model to achieve spatial discretization [18]. The fluid temperature was reduced to 10 K [19]. A total of 18 iterations were performed. For determining the average radiation intensity on the surfaces of whole and mango spears, the average times to reach convergence in Fluent software (Academic Student Version 2019 R3) were 320.180 s and 123.748 s, respectively. The simulations were executed on an Intel Core TM i5-1035G1 CPU (1.19 GHz) with 8 GB of RAM.

2.6. Simulation Study

To identify the orientation at which whole and minimally processed mango received the most uniform irradiation and the highest amount of radiant energy, the average radiation intensity was assessed on three surfaces: the adjacent surface to the lamp (AS); the underexposed surface (US) (which is not directly affected by UV-C radiation) of mango spears; and the total surface (TS) of both whole and minimally processed mango using CFD-Post (Academic Student version 2019 R3, ANSYS Inc., San Jose, CA, USA). Additionally, the area-weighted uniformity index (UI) was calculated using Fluent software.

2.7. Inactivation Models

The impact of UV-C treatment on the surface of both whole and minimally processed mangoes was simulated, incorporating inactivation models for the foodborne pathogens *Salmonella* Typhimurium (Equation (2)) and *Escherichia coli* O157:H7 and *Listeria monocytogenes* (Equation (3)), as identified by Garzón-García et al. [20]. CFD simulations showed UV-C intensity distribution on the fruit surfaces, while kinetic parameters and average intensity on TS of whole and minimally processed mango were used to predict the estimated time and required doses to achieve one to three logarithmic reductions in foodborne pathogen inactivation on the fruit surface.

$$\log_{10}(N/N_0) = -k'It/2.303, \tag{2}$$

$$\log_{10}(N/N_0) = -(1/2.303)\left(It/\alpha'\right)^{\beta}, \tag{3}$$

where N and N_0 are population count over time and the initial population count, respectively. k' denotes the modified inactivation rate (m^2/kJ); I stands for the average radiation intensity on the surface determined through CFD simulations (kW/m^2); t is the treatment time (s), and the value of 2.303 corresponds to $\ln(10)$. β describes the shape of the curve; α' is the modified scale parameter (kJ/m^2). The kinetic parameters for *E. coli* and *L. monocytogenes* were considered as $\alpha' = 0.011$ kJ/m^2; $\beta = 0.312$; $\alpha' = 0.489$ kJ/m^2; $\beta = 0.543$, respectively. For *S.* Typhimurium, $k' = 0.736$ m^2/kJ.