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Design and optimization through simulation of an industrial system for the continuous UV-C treatment of fruits and vegetables

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Abstract

Food loss and food waste are critical issues worldwide, and they have been largely addressed by institutions in recent years. Horticultural products are particularly prone to experience decay and loss of quality, so they often happen to be disposed of without being consumed. The treatment of food products with Ultraviolet (UV) light in the UV-C region, can contribute to extending the product shelf-life by decreasing the surface microbial and fungal contamination, and by activating stress-induced defense mechanisms (hormesis). Despite being effective, energy-efficient and non-toxic, the irradiation of fruits and vegetables is not widespread in the food industry, mainly due to technical and legislative limitations.

In this paper we use a simulation approach to define technical guidelines for the design and the optimization of a machine for the continuous treatment of fruits and vegetables with UV-C rays, aiming to improve the uniformity of the radiation dose imparted to the products and decrease the processing time. The goal of our study, therefore, is three-fold: (*i*) to contribute to the state-of-the-art of UV-C treatment of horticultural products; to define technical guidelines that would (*ii*) optimize both the device and the process, and (*iii*) make the UV-C treatment effectively implementable by industrial stakeholders.

Keywords: ultraviolet radiation, fruit and vegetable treatment, microbial inactivation, numerical simulation, shelf life

1. Introduction and state of the art

Food loss and food waste are critical issues worldwide. A target for the reduction of food loss and waste, to be achieved by 2030, has been set by the United Nations (UN) within the scope of the Sustainable Development Goal (SDG) 12, relating to Responsible Consumption and Production (UN, 2015). These issues have been also addressed in a recent annual Food and Agriculture Organization (FAO) report on the State of Food and Agriculture, titled "Moving forward on food loss and waste reduction" (FAO, 2019). Because of their highly perishable nature, horticultural products, i.e., fruits and vegetables, are particularly prone to losing quality and decay over time, thus they often must be disposed of without being consumed. When this happens, besides the direct disposal of the food products, all the resources that have been used for their cultivation, packaging, transportation, and storage are also wasted. There is a need, therefore, for techniques that would allow for an extension in the shelf-life of the products, while minimizing the resources employed throughout the production cycle.

One factor that greatly contributes to the decay of fruit and vegetables is the presence of microbial and fungal contamination on their surfaces. To reduce to a target level the superficial contamination of the products, decontaminating treatments are a possible solution. Traditional surface disinfection approaches, however, usually involve the use of chemical agents, which may leave residuals and by-products harmful to human health (Gadelha et al., 2019).

Ultraviolet (UV) light has been used for a long time for the disinfection of air, water, and surfaces (Silva et al., 2013; Nguyen et al., 2022). The germicidal effect of the UV treatment is maximum at the wavelength of 253.7 nm, in the UV-C region, and it is proportional to the radiation dose, intended as the amount of energy supplied to a point over time. In the literature, the inactivation UV-C doses and the rate constants are available for a wide range of bacteria, viruses, and fungi. (Kowalski, 2009). In the last decades, the use of UV-C has been extended to food products, both solid and fluid, due to its several advantages. The treatment with UV-C radiation, indeed, is a non-chemical and non-thermal decontamination technique that does not leave residual by-products, and has also the advantages of being effective, cheap, energy-efficient, and easy to implement. (Guerrero-Beltrán and Barbosa-Cánovas, 2004; Vignali et al., 2022). One important limitation is the low penetration ability of the UV-C rays (Olaimat and Holley, 2012): decontamination, therefore, can be effectively achieved only on the surfaces exposed to radiation.

Researchers have extensively evaluated the effects of the superficial decontamination of fruit and vegetables with UV-C radiation on product safety and quality, proving its effectiveness in extending the product shelf-life while minimizing quality losses and side effects (Darré et al., 2022; Singh et al., 2021; Sethi et al., 2018). In addition, several studies have investigated the stress-induced hormesis response, caused by the exposure of the products to radiation, which can improve the resistance to microorganisms, delay ripening and, overall, increase the shelf-life and nutritional quality. (Duarte et al. 2020). It is important, however, to treat the products with a uniform radiation dose, to achieve a uniform level of decontamination and avoid overexposure that may cause the products' quality to decrease (Pandiselvam et al, 2022).

Nowadays UV-C radiation is employed in the food industry mainly to control mold and bacteria contamination in food processing facilities, while its implementation in continuous inline treatments of food products is not widespread, with the main causes being legislative and technical. Regarding the regulations, the United States Food and Drug Administration (USFDA) has approved the use of UV-C irradiation for the decontamination of food products and juices (USFDA, 2000). In Europe, however, surface decontamination with UV-C is allowed only for certain food categories, such as bread, baker's yeast, mushrooms, and milk (EU Regulation 2017/2470). To broaden the scope of the treatment, authorizations must be requested from the local governments, with a clear definition of the products treated and the effects of the irradiation.

Regarding the industrial implementation, assuming that the UV-C treatment of the products of interest is permitted in the country where they should be consumed, Shama (2007) has outlined the basic requirements that a system for irradiating fresh produce should satisfy. These include the following: (*i*) the UV dose imparted to the products must be easily measurable and tunable; (*ii*) the process must be economically efficient; the device adopted for the irradiation should allow for high throughputs (*iii*) of, ideally, a wide variety of products (*iv*) that should not be subjected to mechanical damage during the process (*v*). Also, it is essential to guarantee the safety of the operators, as the exposure of humans to UV-C radiation leads to acute harmful effects, targeting mainly the skin and the eyes (Zaffina et al., 2012).

To facilitate the adoption of UV-C for the treatment of food at an industrial level, and its integration in continuous processing lines, the process itself must be optimized to guarantee the uniformity of the dose distribution on the product surface and reduce the processing times. To this end, simulation tools can be used to develop digital models of industrial systems (Chryssolouris et al., 2009). These models could be used to develop Digital Twins of the systems, that would realistically replicate the functioning of the plants by including a wide range of experimental variables and conditions, and allow for the evaluation of different what-if scenarios without wasting time and resources on physical implementations and tests (Boschert and Rosen, 2016).

Numerical simulation, e.g., Computational Fluid Dynamics (CFD) and multi-physics simulation, has been widely used to optimize several food-processing treatments and plants (Oyinloye and Yoon, 2021; Malekjani and Jafari, 2018; Park and Yoon, 2018), both in design and operating phases. The simulation of the irradiation of liquid foods has been addressed in the literature to reproduce and optimize the functioning of thin-film UV reactors (Buhler et al., 2019). To date, however, only a few studies have used a simulation approach to investigate and optimize a device for the continuous UV-C treatment of solid food products (Kingwascharapong et al., 2020; Tanaka et al., 2016). In particular, the authors used numerical simulation to optimize the configuration, in terms of geometry, number and position of lamps and reflectors, of a machine used to irradiate strawberries placed on a polymeric tray.

In this paper we deal with the design and the optimization of a machine for the continuous UV-C treatment of horticultural products, composed of an external stainless-steel tunnel, a conveyor belt, and a number of UV lamps displaced above and under the conveyor belt. We adopt a simulation approach to improve the uniformity of the radiation dose imparted to the products' surface and decrease the processing time.

The goal of our study is three-fold: (*i*) to contribute to the state-of-the-art by increasing the knowledge about the continuous superficial UV-C treatment of fruits and vegetables, and (*ii*) to define technical guidelines for an efficient design and management of both the device and the process. Finally, (*iii*) we aim to encourage the adoption of the UV-C radiation for superficial decontamination of horticultural products by industrial stakeholders and, consequently, to generate the need for the development of specific legislation.

2. Materials and methods

2.1. Nomenclature

The symbols and the abbreviations adopted in the paper are summarized below in Table 1. For the sake of brevity, the solid horticultural food products will be referred to as "fruits" in the text.

Table 1. Symbols and abbreviations adopted in the paper.

Term	Description
n_L	number of lamps
d_{LL}	distance between two consecutive lamps
d_{ff}	distance between two consecutive fruits
d_{LF_y}	vertical distance between the row of lamps and the products
r	distance from the radiation source
α_{254}	absorption coefficient of the medium at 254 nm
D_L	diameter of the lamp
L_L	length of the lamp
D_f	diameter of a spherical fruit
P_L	lamp wattage
$P_{L,254}$	UV output at 254 nm
I_0	intensity of radiation at the source
I	intensity of radiation at a generic distance from the source
D	radiation dose
x	distance along the x-axis, i.e., position
t	treatment time

2.2. Device for the UV-C treatment of solid foods

In this study, we aim to design and optimize, with the aid of numerical simulation, a device for the continuous UV-C treatment of solid food products, in particular fruits and vegetables.

The main structure of the device is defined according to the peculiar characteristics of the treatment and the products, and consists of the following elements:

- A continuously-moving conveyor belt, on which the products are placed;
- One row of lamps above the conveyor belt (top lamps);
- One row of lamps below the conveyor belt (bottom lamps);
- An external stainless-steel tunnel.

In the case of solid food products, UV-C radiation can achieve only surface decontamination so, in the device considered, two rows of lamps are assumed to be installed above and below the conveyor belt to provide a uniform radiation dose on the whole product surface. For the same reason, the conveyor belt must have large open areas, to allow the radiation emitted by the bottom lamps to reach the fruits. The purpose of the external stainless-steel enclosure is two-fold: (*i*) to protect the products from the environment and possible re-contamination and (*ii*) to protect the operators from being exposed to harmful radiation.

Regarding the conveyor belt running direction, the arrangement of the lamps can be longitudinal or transversal. In this study, a transversal layout of UV-C lamps is investigated, differently from the configuration adopted by Kingwascharapong et al. (2020) and Tanaka et al. (2016). The main reasons for this choice were:

- Ease of maintenance: transversally oriented lamps can be easily extracted and replaced from the side of the machine;
- Flexibility in defining the length of the device: in the case of longitudinal lamps, the length of the machine is constrained to the length of the lamp.

To design an efficient UV-C treatment, it is important to guarantee that the product's surface receives a dose of radiation as uniform as possible, and sufficient to achieve the intended effect even in the least irradiated points. The dose depends both on the intensity of the radiation that reaches the product's surface and on the treatment time. It is calculated as follows:

$$D = \int I \, dt \tag{1}$$

Where *I* is the intensity of the radiation at a generic distance from the source. *I* is inversely proportional to the square of the distance from the light source, and it attenuates as a function of the absorption coefficient of the medium it passes through (in our case air) according to a negative exponential law:

$$I \propto \frac{I_0}{r^2} \cdot \exp\left(-\alpha_{254} \cdot r\right) \tag{2}$$

From Eq. 2 emerges that the intensity decreases rapidly, as the distance from the source increases.

2.2.1. *Lamps*

The features of the commercial amalgam UV-C lamps considered in this study are listed in Table 2.

Table 2. UV-C lamp features.

Term	Value	Units
D_L	15	mm
L_L	843	mm
P_L	105	W
$P_{L,254}$	31.5	W

2.3. Numerical simulation

The distance between fruits affects the degree of filling of the conveyor belt, hence the productivity of the machine. The impact of three different product layouts on the dose supplied to the products was evaluated using a simulation approach and Ansys®, Release 2021 R2 software. The geometrical features considered are summarized in Table 3.

Table 3. Geometrical features of the fruits and layouts considered.

Term	Value	Units
D_f	50	mm
n_{L_TOP}	5	-
n_{L_BOTTOM}	4	-
d_{LL}	150	mm
d_{ff_1}	25	mm
d_{ff_2}	37.5	mm
d_{ff_3}	50	mm
d_{LF_y}	40	mm

To perform the simulations, the first step consisted of the modeling of the geometry (Figure 1). To decrease the computational cost of the simulation, the conveyor belt was not considered at this point. Instead, the effect of its presence was included directly during the simulation setup. The external walls of the stainless-steel tunnel were neglected as well, as they were not essential to the evaluation performed. The geometry was created as follows:

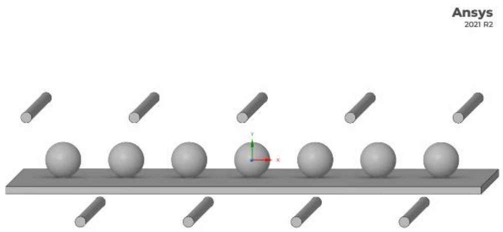

Figure 1. Schematic representation of the components inside the device.

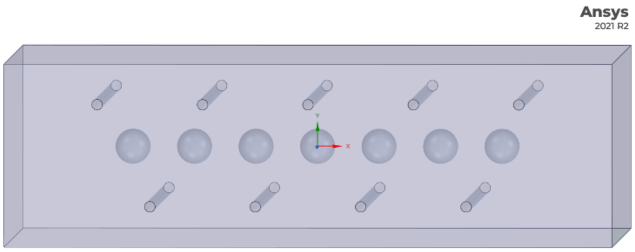

Figure 2. 3D simulation domain, consisting of an enclosure surrounding the fruits and the lamps.

- Generation of the 3D model of the system components: top lamps, bottom lamps, a row of spherical fruits positioned orthogonally to the lamps, in the mid-position;
- Generation of an enclosure around the system modeled;
- Subtraction of the fruits and lamps bodies from the enclosure.

The domain, therefore, consisted of the volume of air surrounding the system components (Figure 2).

Radiation boundary conditions were defined both for the fruits and the lamp. The fruits were set as "opaque" bodies, while the lamps were set to be "semi-transparent", with uniform diffusion in all directions. The radiation intensity per unit area of the lamps was calculated as the ratio between their UV output at the wavelength of 254 nm and the surface area. To account for the presence of the conveyor belt with large open areas, the intensity of radiation of the bottom lamps was multiplied by 0.8. Discrete Ordinates (DO) radiation model was then used to compute the radiation field in the domain simulated and calculate the intensity of UV-C imparted to the surface area of the fruits.

The simulations were carried out under steady-state conditions to obtain more stable results compared to transient conditions. Three different fruit layouts were modeled, by setting the distance between the fruits to the value of d_{ff_1}, d_{ff_2}, and d_{ff_3}. The simulations were replicated after moving the fruits along the x-axis by a distance of $(D_f+d_{ff})/2$, to evaluate more intermediate positions. Minimum and maximum values of radiation intensity were calculated on each fruit surface.

3. Results and discussion

The results of the simulations, in terms of graphical representation of the intensity of radiation on the surface irradiated, are presented in Figure 3. The top and bottom views of the fruit surfaces are presented in Figure 4.

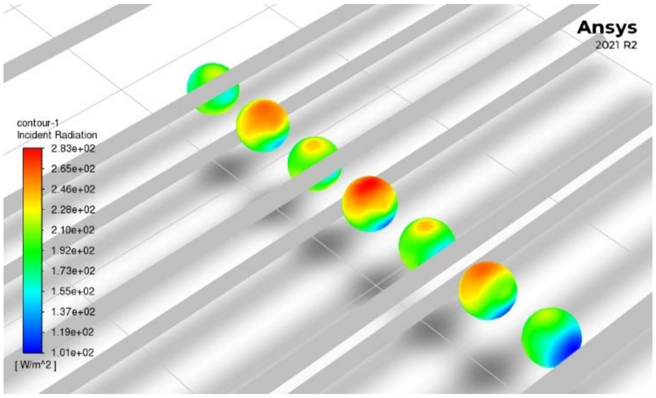

Figure 3. Contour plot of incident radiation on the fruit surfaces, with a distance of 25 mm between consecutive fruits.

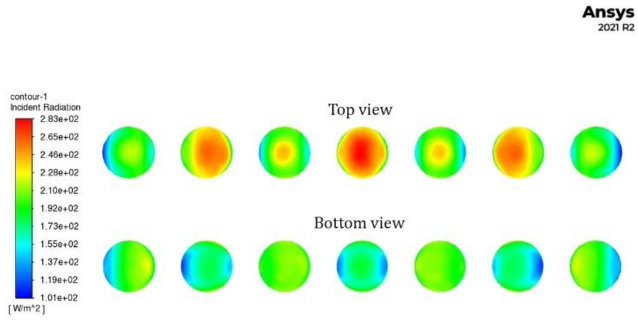

Figure 4. Contours on incident radiation on the top side (above) and bottom side (below) of the products treated, with a distance of 25 mm between the fruits.

These contour plots allow for assessing the magnitude of the radiation intensity imparted, and for locating the zones where it reached its maximum and minimum values. The most irradiated regions generally occurred on the top part of the fruits, while the least irradiated areas were on the sides, where the points furthest from the lamps were located. Since the irradiation from the bottom lamps was attenuated by the presence of the conveyor belt, the least treated areas resulted to be on the lower halves of the fruits.

Maximum and minimum values of radiation intensity were recorded for each fruit surface, in several relative positions to the lamps. In this way, although the simulations were carried out under steady-state conditions, the results obtained made it possible to evaluate the intensity of the radiation delivered to the products at several locations across the device. In Figure 5, Figure 6 and Figure 7, the values of minimum and maximum radiation in the case of different distances between the products are plotted against the position x, referring to the center points of the fruits. In the graphs, the positions of the top lamps are represented with solid black lines, while the bottom lamps are indicated by dashed black lines.

As expected, the maximum values of radiation intensity were located on the top part of the surfaces, when the fruits were directly under a top lamp.

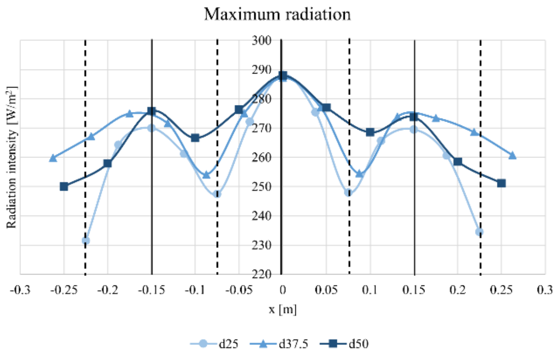

Figure 6. Maximum radiation imparted to the fruits, in the case of different fruit layouts.

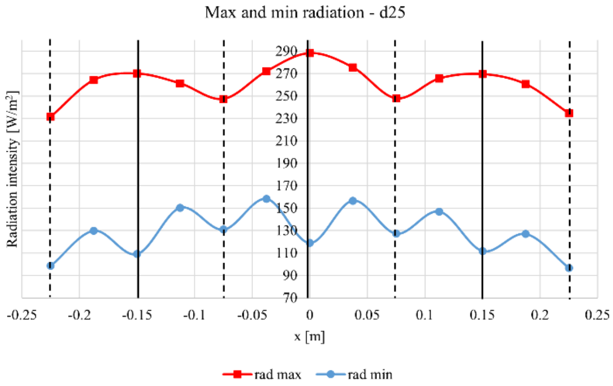

Figure 5. Maximum and minimum radiation with a distance of 25 mm between the fruits.

Furthermore, the intensity increased as the fruits were closer to the central part of the device, where the effects of multiple lamps overlapped. On the other hand, a decrease in the radiation intensity was observed in the parts of the device near the borders, where the superposition of the effects of the lamps was much lower.

The lowest values of radiation intensity occurred when the fruits were located either directly below or above a lamp. This is explained by the fact that, in these positions, the less irradiated areas, located on the sides of the fruits, did not receive the contribution of the closest lamp.

Concerning the effect of the disposition of the fruits on the belt, it appears that greater distances between the products led to higher values in both maximum and minimum radiation intensity. Since the dose imparted to the fruits depends on the radiation intensity and the treatment time, in the case of a belt densely filled with products longer exposure time would be required to deliver the same target dose to the products. To optimize the productivity of the device, therefore, an optimal trade-off between the filling degree of the belt and the duration of the treatment should be determined.

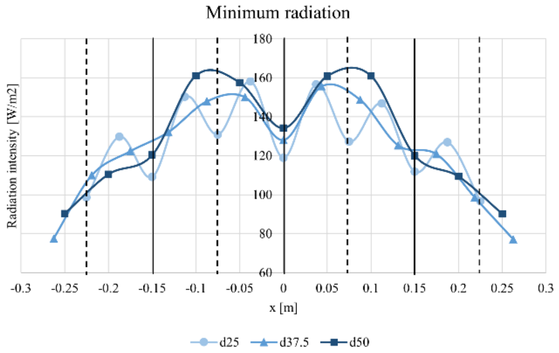

Figure 7. Minimum radiation imparted to the fruits in the case of different fruit layouts.

4. Conclusions

In this study, we used a simulation approach to deal with the design and the optimization of a machine for the continuous UV-C treatment of fruits and vegetables. This treatment became of great interest in recent years, as it allows for surface decontamination of the products and induces a beneficial hormetic response, while minimizing the energy consumption and not leaving any potentially harmful residuals and by-products.

The device proposed in this study is composed of a continuously running conveyor belt, two rows of lamps installed above and below the belt and arranged transversely to its running direction, and a stainless steel tunnel to enclose all the components. The analysis performed contributes to the state-of-the-art of industrial implementation of UV-C radiation for solid food products, by assessing the impact of the processing parameters on the treatment. Also, the arrangement of the lamps proposed appears to be more efficient, in industrial applications, compared to the longitudinal configuration, as it increases the ease in maintenance and replacement of the lamps and allows for a more flexible sizing of the machine.

The research was carried out by performing numerical simulations of the device and using the discrete ordinates (DO) model to compute the radiation field inside it. Three fruit layout configurations were evaluated to assess the impact of the distances between fruits on the effectiveness of the treatment. It was found that, as the distance between the fruits decreased, so did the intensity of the radiation reaching its surface, due to a greater presence of interfering bodies and shadows. Due to this, to impart the target dose to the products, a longer exposure time would be required in the case of a belt more densely filled with products. Future research activities should include the simulation of more rows of fruits, to further investigate the effects of the filling degree in the device on the treatment.

The results of the simulations also highlighted the superposition of the effects of adjacent lamps, leading to higher doses in the central part of the device and lower values near the borders of the machine. This "border effect" is expected to occur both in parallel and transverse directions to the product flow, and it must be investigated in future research activities to correctly and efficiently size the device.

Other research activities that should be carried out include the investigation through simulation of the variation of the geometric parameters of the device, such as the distance between the fruits and the lamps, the distance between the lamps, and the comparison between longitudinal and transverse lamp arrangements. Also, it will be essential to validate the model developed with experimental tests and confirm its validity as a tool for the design and optimization of the device. Furthermore, it will be interesting to perform shelf-life studies and microbiological counts on the products treated to assess the effects of different configurations on different products.

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