Original paper

Simulation of UV-C Intensity Distribution and Inactivation of Mold Spores on Strawberries

Vipavee TRIVITTAYASIL¹, Fumihiko TANAKA^{2*} and Toshitaka UCHINO²

¹Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan

²Laboratory of Postharvest Science, Faculty of Agriculture, Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan

Received September 7, 2015 ; Accepted December 22, 2015

The practical usage of UV-C to decontaminate fruits has been limited by the difficulty applying a uniform dose to complicated shapes. Simulation of UV-C radiation treatment was investigated in this study to find the optimal treatment conditions. A setup of strawberries being placed on a UV-transmittable film with radiation sources from the top and bottom was proposed. A 4-lamp model with a horizontal distance of 300 mm between the lamps was found to yield the most uniform dose distribution, with mean radiation intensity of 2.00 W m^{-2} . For this configuration, the treatment time required to achieve one log inactivation of *Cladosporium cladosporioides* and *Penicillium digitatum* spores were 3 min 46 s and 1 min 36 s, respectively. Radiation simulation in combination with the inactivation model has been shown to be a useful tool for the optimization of the UV-C inactivation process.

Keywords: UV-C, CFD, strawberries, surface decontamination, DO model

Introduction

A considerable amount of fruits and vegetables are lost during postharvest, processing and distribution processes (FAO, 2011). To reduce the loss due to fungal decay, various postharvest treatments such as surface decontamination should be implemented. There are many types of surface decontamination techniques available; however, most methods involve the use of chemicals (Beuchat, 1998). Due to a growing concern over the effect of chemical residues on human health, alternative physical techniques such as UV-C irradiation have received attention in recent years.

UV-C radiation has a wavelength ranging from 100 to 280 nm and is known to be highly germicidal. The use of UV-C radiation as a non-chemical surface decontamination treatment of fresh fruits has several merits. It is cheap, easy to operate and can be readily incorporated in the processing line. The inactivation effect of UV-C radiation has been investigated in many agricultural products

such as fresh-cut apples (Manzocco *et al.*, 2011), baby spinach (Escalona *et al.*, 2010), peppers (Vicente *et al.*, 2005) and strawberries (Marquenie *et al.*, 2003). Nevertheless, one obstacle which has been slowing down the practical implementation of UV-C is the difficulty in achieving a uniform irradiation dose on complicated surfaces.

There are many reasons a uniform irradiation dose is desired for UV-C treatment. Firstly, uniform dose distribution is needed to achieve an even level of inactivation. Secondly, overexposure to UV-C could degrade the quality of the fruits. Thus, the range of dose intensity should be as narrow as possible to avoid applying too much radiation. Potential damage to strawberries under high UV-C dose includes browning of the calyx (Lammertyn *et al.*, 2003). Thirdly, the inactivation effect of UV-C on fruits is found to increase with UV-C dose initially but then begins to diminish after exceeding a certain threshold (Nigro *et al.*, 2000; Stevens *et al.*,

*To whom correspondence should be addressed.

E-mail: fumit@bpes.kyushu-u.ac.jp

Nomenclature

a	absorption coefficient, m^{-1}	<i>Greek symbols</i>	
I	radiation intensity, which depends on position ($\vec{r}$) and direction ($\vec{s}$), W m^{-2}	σ	Stefan-Boltzmann constant ($5.669 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$)
n	refractive index	σ_s	scattering coefficient, m^{-1}
p	pressure, Pa	Φ	phase function
T	temperature, K	Ω'	solid angle

1996). Hence, delivering the optimal dosage with uniform dose distribution is important to successfully implement UV-C treatment of fruits.

Recent advancement in numerical methods has enabled simulation of complex problems in food processing. One of the many applications in numerical methods is the use of computational fluid dynamics (CFD) modeling. CFD modeling has been gaining popularity among researchers in the food industry (Scott & Richardson, 1997). The application of combined flow and heat transfer in food processing has become increasingly accurate due to advances in modern computing power (Norton & Sun 2006). The modeling of a complex 3D shape has benefited from recent development as confidence in its predictions has greatly improved. Examples of its implementation include modeling heat transfer and moisture loss in bagged potatoes during cold storage (Chourasia & Goswami, 2007), modeling heat transfer of infrared heating on strawberries (Tanaka *et al.*, 2007), predicting 3-D dose distribution of electron beam radiation treatment of complex foods (Kim *et al.*, 2007), and simulating radiation distribution and inactivation in wastewater treatment (Crapulli *et al.*, 2010; Elyasi *et al.*, 2006). CFD modeling has proved to be a powerful engineering tool, providing an efficient and effective design solution. The success of using CFD modeling in the prediction of UV treatment for water needs to be tested on decontamination of fruits. The use of CFD modeling to predict radiation intensity will be tested here and compared with experimental values. The developed model will help in optimizing various decontamination treatment conditions.

Materials and Methods

(1) *Radiation model* The discrete ordinate (DO) radiation model uses a transport equation to calculate the radiation intensity in the spatial coordinates. It solves as many transport equations as there are direction vectors associated with a number of discrete solid angles. The DO model calculates radiation intensity as a function of absorption, scattering, reflection, and emission. The radiative transfer equation in the direction $\vec{s}$ for the DO model is shown below.

$$\nabla \cdot (I(\vec{r}, \vec{s}) \vec{s}) + (a + \sigma_s) I(\vec{r}, \vec{s}) = an^2 \frac{\sigma T^d}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \Phi(\vec{s} \cdot \vec{s}') d\Omega' \quad \dots\dots\text{Eq. 1}$$

The advantage of the DO model is its ability to account for semi-transparent media and to consider participating media (air) in addition to radiation at the surface. Its accuracy can also be increased by using a finer angle discretization. For the

completeness of the mathematical description, a set of boundary conditions was defined on the physical surfaces and domain walls, with important parameters indicated in Table 1.

(2) *Validation study* Two simulation models (models A and B) in Fig. 1 featuring simple cases of radiation transfer were created to test the accuracy of the simulation. Model A was created based on actual equipment while model B was built based on an ideal condition which only considers radiation transfer from a lamp, excluding the effect of radiation reflection by the lamp cover. The pilot apparatus consisted of a 6 W UV-C lamp (GL-6, Toshiba) for both models and a lamp cover (FL-06003-SL16, Toshiba) only for model A. The calculated intensity of the middle point of model A was compared with the measured values at different irradiation distances. To obtain the measured values, a UV meter (UVC-254, Custom) was placed directly below the lamp to measure the incident radiation intensity at distances of 50, 75, 100, 125, 150, and 187.75 mm from the lamp. The lamp was allowed to stabilize for at least 3 min before measurement to achieve a constant lamp intensity. Model B was used for a mesh sensitivity test, in which models with different mesh numbers were used for calculations. The calculated radiation intensity along the middle line of each model was compared to find the mesh-independent conditions. After performing the mesh sensitivity test, the accuracy of calculated UV intensity was compared with mathematical equations as described below.

According to Danno *et al.* (1981), the direct UV intensity, E_p , falling on the center point on the bottom wall can be calculated using Eq. 2.

$$E_p = 2 \int_0^{\frac{L}{2}} \frac{dI_\theta \sin \theta}{d^2} dz = \frac{L dI_\theta}{h \sqrt{h^2 + L^2}} \quad \dots\dots\text{Eq. 2}$$

As Eq. 2 only calculates the intensity at the middle point, the following equations were introduced to calculate the intensity of other points parallel to the lamp length as shown in Fig. 2.

$$\begin{aligned} E_k &= \int_0^{z_k} \frac{dI_\theta \sin \theta}{d_1^2} dz + \int_0^{z_{L-k}} \frac{dI_\theta \sin \phi}{d_2^2} dz \\ &= \int_0^{z_k} \frac{dI_\theta h}{d_1^3} dz + \int_0^{z_{L-k}} \frac{dI_\theta h}{d_2^3} dz \\ &= dI_\theta h \left(\frac{zk}{h^2 \sqrt{h^2 + z_k^2}} + \frac{z_{L-k}}{h^2 \sqrt{h^2 + (z_{L-k})^2}} \right) \quad \dots\dots\text{Eq. 3} \end{aligned}$$

where k is the distance of the point from one end of the lamp and $\sin \theta = h/d_1$ and $\sin \phi = h/d_2$. Eq. 3 was employed to calculate the incident radiation intensity at points along the middle line of model B.

(3) *Simulation study* The effects of various parameters on the

Fig. 1. Schematic diagrams of models A and B

Table 1. Model parameters and their adopted values

Parameter	Value
Absorption coefficient of LLDPE [m^{-1}] ^a	274
Density of air [kg m^{-3}] ^b	1.225
Density of LLDPE [kg m^{-3}] ^c	930
UV power of lamp [W] ^d	1.7
Emissivity of lamp ^e	0.89
Emissivity of lamp cover ^f	0.04
Emissivity of strawberry ^g	0.95
Refraction index of LLDPE ^c	1.525

^ameasured value, ^bFluent software database, ^cJapan Society of Thermophysical Properties Handbook (1990), ^dreported by the manufacturer, ^eCoussirat *et al.* (2008), ^fIncropera (2001), ^gTanaka *et al.* (2007)

UV-C dose distribution of strawberries were investigated. Firstly, a study was conducted to find the most suitable orientation of a strawberry when irradiated by a single lamp. The objective was to find the optimal orientation allowing the largest strawberry area to be irradiated without rotating it. The geometry was built based on radiation equipment comprised of a UV-C lamp, a cover and a strawberry. An average-sized *Amao* strawberry was chosen as the raw material for 3D image acquisition. The image of the strawberry was obtained by a 3D laser scanner (Next Engine, USA). The equipment consisted of a calibrated camera, a rotation table, a laser source and a computer with ScanStudio HD software (Next Engine, USA). Scanning, aligning, trimming, filling holes and fusing are the main processing features used to produce a single surface mesh. The image acquisition process and the strawberry surface obtained are shown in Fig. 3a and 3b. The distance from the lamp surface to the base of the strawberry was 150 mm. Three geometries were created with the strawberry calyx on its side, top, and bottom (Fig. 4a).

Secondly, the effect of the number of lamps and their positions on nine strawberries placed on a film tray (B9, Yurikago, Ohishi

Fig. 2. Calculation of the radiation intensity (E_k) at a point under the UV lamp

Fig. 3. Acquisition of 3D image of a strawberry using 3D scanner (a), obtained surface mesh (b) and nine strawberries on the film tray (c)

Sangyo Co. Ltd.), which was made of linear low-density polyethylene (LLDPE), was investigated. A film tray was introduced because it allowed partial UV-C radiation to pass

Fig. 4. Geometries with three orientations of strawberries (a), different numbers of lamps (b) and different horizontal distances for the 4-lamp model (c)

through and can hold up to nine fruits (Fig. 3c). In the simulation setting, strawberries were placed on the tray with the radiation sources at the top and bottom. The geometry was built based on equipment comprised of UV lamps, lamp covers, nine strawberries and a film tray. Geometries with different numbers of lamps ($n = 2, 4, 8$) were created (Fig. 4b). For the 4-lamp model, different horizontal distances between lamps ($d = 150, 200, 250, 300, 350, 400, 450$ mm) were also created (Fig. 4c). The vertical distance from the top lamps to the film tray and the bottom lamps to the film tray was determined such that the intensity from top and bottom lamps reaching the film tray would be approximately equal. This can be done by considering the UV-C absorption coefficient of the film tray as described below.

$$UVT = I/I_0 \quad \dots\dots Eq. 4$$

where UVT is the UV transmittance and I/I_0 is the reduction in intensity. The UV transmittance of the film tray was 0.76 as measured by the UV meter (*UVC-254*). Due to the partial transmittance, the radiation distance had to be adjusted to keep the radiation intensity reaching the samples from the bottom lamp to be the same as from the top lamp. The distances can be calculated using the following equation.

$$\frac{UVT_1}{UVT_2} = \frac{l_1^2}{l_2^2} \quad \dots\dots Eq. 5$$

where l is the distance from the radiation source.

(4) DO simulation The geometries were created using ANSYS Workbench 14.0 software (ANSYS Inc., USA). They were meshed using the automatic meshing method. Mesh inflation and mesh refinement were applied to major boundaries. The simulation was calculated using Fluent 14.0 software (ANSYS Inc., USA), employing a DO radiation model with theta and phi divisions of 10×10 and theta and phi pixels of 3×3 to solve the radiative transfer equation in the computational domain. Aside from the domain, the volumes inside the lamp, lamp cover and strawberries were left blank, as their internal heat transfer was of no interest in

this study. The steady-state governing equation was solved using the SIMPLE algorithm and the spatial discretization was solved by the first order upwind method for the DO model.

(5) Inactivation model The inactivation effect of UV-C on the strawberry surface can be simulated by incorporating the inactivation model with the radiation transfer model. While the radiation transfer model provides information on UV-C intensity at each spatial position of the strawberry surface, the inactivation model offers information on the degree of inactivation when treatment intensity and time are known. Inactivation models of common mold spores on fruits by UV-C have been previously investigated on an agar surface (Trivittayasil *et al.*, 2015). The inactivation of *Cladosporium cladosporioides* and *Penicillium digitatum* spores was respectively found to follow a biphasic linear model and a first order model, as follows.

Cladosporium cladosporioides:

$$\log_{10} S = \log_{10}[(1-f) \cdot 10^{-\frac{It}{D'_{sens}}} + f \cdot 10^{-\frac{It}{D'_{res}}}] \quad \dots\dots Eq. 6$$

Penicillium digitatum:

$$\log_{10} S = -\frac{k'It}{2.303} \quad \dots\dots Eq. 7$$

where S is the survival rate, I is the average irradiation intensity on agar (kW m^{-2}), t is the treatment time (s), $1-f$ and f are the fraction of the population that is treatment-sensitive and treatment-resistant, with modified D values of D'_{sens} (kJ m^{-2}) and D'_{res} (kJ m^{-2}), respectively, and k' is the modified inactivation rate constant ($\text{m}^2 \text{kJ}^{-1}$). The parameters for *Cladosporium cladosporioides* were $f = 0.00136$, $D'_{sens} = 0.45 \text{ kJ m}^{-2}$ and $D'_{res} = 13.55 \text{ kJ m}^{-2}$, whereas the parameter for *Penicillium digitatum* was $k' = 11.98 \text{ m}^2 \text{kJ}^{-1}$. These parameters were determined by fitting the inactivation curve with various models using the least squares method.

Results and Discussion

(1) Model validation

a) Model A The accuracy of the calculated radiation intensity was investigated using model A. Initially, a simulation based on the declared UV power from the lamp manufacture was performed. However, the predicted values were higher than the measurements. This phenomenon likely resulted from the actual UV-C power of the lamp being lower than the declared value, which is often due to not taking into account lamp efficiency and a decreasing power output throughout the shelf life of the lamp. The efficiency ratio of the lamp was thus calculated by measuring the maximum intensity directly under the lamp at various distances. By considering the efficiency ratio of the lamp, the modified UV power, whose value is closer to the real value of the lamp, can be obtained.

$$W' = \eta W \quad \dots\dots Eq. 8$$

where W' is the modified lamp power (in W), W is the declared lamp power (in W), and η is the nominal efficiency ratio. The nominal efficiency ratio was calculated to be 0.48. The simulation

Fig. 5. CFD model validation: comparison between measured and predicted radiation intensity of the center point of model A (a) and comparison of predicted radiation intensity with calculated value by eq. 3 of model B along the middle line (b)

was performed again using the modified UV power. The simulation result was found to fit well with the measurements, with a root mean square error of 0.5315 W m^{-2} (Fig. 5a).

b) Model B A mesh sensitivity test was carried out using model B to determine the adequacy of the mesh quality produced by the automatic meshing method. The default automatic meshing method yielded 93,838 mesh elements. The manual setting was configured to produce smaller and larger mesh elements than the default setting, resulting in 839,219 and 18,110 mesh elements, respectively. The effect of the number of mesh elements on the numerical results is shown in Fig. 6. Although a significant difference in radiation intensity value was observed between the results of 18,100 and 93,838 mesh elements, no significant difference was observed between 93,838 and 839,219 mesh elements. The default automatic meshing method was shown to be sufficient for this study, as a mesh-independent numerical result was achieved.

The incident radiation intensities at different points along the middle line, as indicated in Fig. 1, predicted by CFD were compared with calculated intensity by Eq. 3 (Fig. 5b). Both predictions had a good fit to each other with RMSE of 0.21 W m^{-2} . This result further validated the potential of using CFD to predict radiation intensity.

Fig. 6. Mesh sensitivity test: calculated radiation intensity along the middle line of model B (as indicated in Fig. 1) with different numbers of mesh elements

(2) Effect of various parameters on UV-C intensity distribution on strawberries

a) Strawberry orientation The effect of strawberry orientation on UV-C intensity distribution was investigated. A single strawberry with three different orientations, described by the calyx position: side calyx, top calyx and bottom calyx as shown in Fig. 4a, was placed directly under a UV-C lamp and the average surface incident radiation on the strawberry surface was calculated. The results are presented in Fig. 7a. The underexposed surface areas, which were nominally defined as the regions that received $\leq 0.5 \text{ W m}^{-2}$ radiation intensity, were 43.9, 55.7 and 51.9% of the total surface area for the side calyx, top calyx and bottom calyx orientations, respectively. The maximum surface incident radiation on the strawberry were 5.13, 6.06 and 5.86 W m^{-2} , respectively. The side calyx position was found to be the most suitable, as it allowed the largest area of strawberry to be irradiated while keeping the maximum incident radiation lowest by comparison to other orientations.

b) Number of lamps For practical implementation of UV-C treatment of strawberries, nine strawberries placed on a tray film with high UV-C transmittance were simulated. This configuration was chosen because it allowed radiation sources from the bottom to penetrate the film, therefore eliminating the need to rotate the fruits during the treatment. The effect of number of UV-C lamps on surface incident radiation intensity was investigated. As shown in Fig. 7b, more lamps increased overall radiation intensity and range. Approximately 18.54, 9.75, and 2.08% of the total strawberry area of the 2-, 4- and 8-lamp models, respectively, were underexposed ($\leq 0.5 \text{ W m}^{-2}$). This result indicated that the underexposed area could not be eliminated by increasing the number of lamps. This underexposed area had to be reduced in order to apply an adequate radiation dose to strawberries. Since the horizontal distance between lamps of this model was relatively short (36.5 mm), increasing the horizontal distance between the lamps was expected to help in reducing the underexposed area and

Fig. 7. Frequency polygons of surface incident radiation on a strawberry at various orientations (a), on nine strawberries for different numbers of lamps (b), and various horizontal distances between lamps of the 4-lamp model (c) and resulting coefficients of variation (d)

thus was investigated in the next part of the study.

c) Horizontal distance between lamps Various horizontal distances between the lamps of the 4-lamp model were investigated (Fig. 7c). The results showed that increasing horizontal distance

Fig. 8. Contours of the surface radiation intensity of the 4-lamp model with horizontal distance between lamps of 300 mm

between the lamps of the 4-lamp model helped to narrow the distribution range of the radiation intensity. A narrow distribution range is desired as it contributes to reducing the risk of overexposure and underexposure. At high horizontal distances of 400 and 450 mm, the underexposed area widened because the lamps became too far away to properly irradiate the inner side of strawberries. To determine the optimal horizontal distance which provides the most uniform dose distribution, the coefficient of variation (CV) was calculated. CV is a normalized measure of dispersion of a probability distribution and can be calculated as follows.

$$CV = \frac{\sigma}{\mu} \quad \text{.....Eq. 9}$$

where σ is the standard deviation and μ is the mean intensity of surface incident radiation (W m^{-2}).

As shown in Fig. 7d, a horizontal distance of 300 mm was found to have the lowest CV value, meaning that the distribution has the smallest spread among other distances tested and thus has the most uniform UV-C distribution compared to other distances. The UV-C dose distribution of the 4-lamp model with a horizontal distance of 300 mm is visualized in Fig. 8. The area-weighted average radiation intensity on all nine strawberries was calculated to be 2.00 W m^{-2} . The minimum and maximum radiation intensity on strawberries was 0.071 and 4.35 W m^{-2} , respectively. Despite having the most uniform distribution under the conditions investigated in this study, the strawberry sides on the edges in the z-axis direction still received lower radiation intensity than other areas. In future study, this underexposed area can be expected to be reduced by employing longer lamps or side reflectors, which also act as barriers to prevent UV-C from reaching operators.

(3) Model-based investigation of inactivation of mold spores on strawberry The time required to inactivate mold spores on the surface of strawberries was calculated for the optimal equipment configuration (4-lamp model with horizontal distance of 300 mm)

Table 2. Estimated time required to achieve inactivation of nine strawberries of the 4-lamp model with horizontal distance of 300 mm between lamps

Mold spores	Estimated time required for inactivation		
	1 log units	2 log units	3 log units
<i>Cladosporium cladosporioides</i>	3 min 46 s	7 min 42 s	16 min 45 s
<i>Penicillium digitatum</i>	1 min 36 s	3 min 12 s	4 min 48 s

Fig. 9. Histograms of estimated survival rate of *Cladosporium cladosporioides* and *Penicillium digitatum* spores at all nodes of strawberry surface after treatment times of 3 min 46 s and 1 min 36 s, respectively

using eqs. 6 and 7. As the inactivation models employed in this study were constructed based on an agar surface, one assumption of was that the inactivation characteristics of spores depend on the irradiation intensity, regardless of the nature of the surface.

The average radiation intensity on all nine strawberries (2.00 W m^{-2}) was used as the average radiation intensity in the equations. Table 2 shows the treatment time required to inactivate one to three logarithmic units of mold spores. In order to achieve an average of one log inactivation of *Cladosporium cladosporioides* and *Penicillium digitatum* spores, treatment times of 3 min 46 s and 1 min 36 s are required, respectively, totaling 0.45 and 0.19 kJ m^{-2} . Although the number of mold spores that needed to be inactivated for treatment to be effective was not investigated in this study, other studies suggested a dose between 0.5 and 4 kJ m^{-2} to decrease naturally occurring decay in fruits (Baka *et al.*, 1999; Nigro *et al.*, 2000; Pan *et al.*, 2004).

As the treatment time in Table 2 was estimated based on average radiation intensity on strawberries, it should be noted that the inactivation level will be lower in the area that receives lower radiation intensity. In the case of an average of one log inactivation, the distribution of inactivation levels across the nodes on the surfaces of nine strawberries is illustrated in Fig. 9. The nodes are connecting points on the strawberry mesh. The surface incident radiation value was obtained for each node and the inactivation level was calculated accordingly.

The treatment time was found to vary greatly between *Cladosporium cladosporioides* and *Penicillium digitatum*. This difference is due to a variation in the inactivation characteristics and rate of inactivation of each species (Trivittayasil *et al.*, 2015).

Thus, for meaningful implementation of UV-C radiation on fruits, it is recommended that the inactivation characteristics of target microorganisms be investigated for each type of fruit to determine the suitable dose.

Conclusion

Optimization of the radiation equipment is the next step to be realized in order for UV-C treatment to be employed in a practical setting. A radiation model by CFD based on actual equipment and specific target samples was constructed and validated in this study. The investigation on the effect of the treatment conditions on radiation intensity distribution on strawberries could be summarized as follows: (1) for a single radiation source from the top, the strawberry orientation with the calyx on its side enabled the most uniform radiation exposure, (2) the usage of the film tray, which was constructed of material that allowed UV-C to partially pass through, helped to radiate strawberries without the need to rotate them, (3) for nine strawberries on the film tray, the best configuration providing the most uniform dose distribution was the 4-lamp model with a horizontal distance between lamps of 300 mm and (4) for the optimal configuration, 3 min 46 s and 1 min 36 s are required to inactivate *Cladosporium cladosporioides* and *Penicillium digitatum* spores by 1 logarithmic unit.

Acknowledgements This research was supported by the Ministry of Education, Science, Sports and Culture of Japan (Project No. 22580289). We would like to sincerely thank Chihiro Imamura and Misaki Tsuru for their invaluable help, and Siri S. Khalsa and Clifford K. Ho of Sandia National Laboratories for their kind explanation regarding DO modeling.

References

- Baka, M., Mercier, J., Corcuff, R., Castaigne, F., and Arul, J. (1999). Photochemical treatment to improve storability of fresh strawberries. *J. Food Sci.*, **64**, 1068-1072.
- Beuchat, L. R. (1998). Surface decontamination of fruits and vegetables eaten raw: a review. Food Safety Unit, World Health Organization. p. 42.
- Chourasia, M. and Goswami, T. (2007). CFD simulation of effects of operating parameters and product on heat transfer and moisture loss in the stack of bagged potatoes. *J. Food Eng.*, **80**, 947-960.
- Coussirat, M., Guardo, A., Jou, E., Egusquiza, E., Cuerva, E., and Alavedra, P. (2008). Performance and influence of numerical sub-models on the

- CFD simulation of free and forced convection in double-glazed ventilated facades. *Energ. Buildings*, **40**, 1781-1789.
- Crapulli, F., Santoro, D., Haas, C. N., Notarnicola, M., and Liberti, L. (2010). Modeling virus transport and inactivation in a fluoropolymer tube UV photoreactor using Computational Fluid Dynamics. *Chem. Eng. J.*, **161**, 9-18.
- Danno, A., Miyazato, M., Ishiguro, E., and Nakayama, T. (1981). Studies on the preservation effect on agricultural products by the irradiation of ultraviolet ray: I. Construction of experimental irradiation apparatus. *Bulletin of the Faculty of Agriculture, Kagoshima University*, **31**, 157-162. (in Japanese)
- Elyasi, S. and Taghipour, F. (2006). Simulation of UV photoreactor for water disinfection in Eulerian framework. *Chem. Eng. Sci.*, **61**, 4741-4749.
- Escalona, V. H., Aguayo, E., Martínez-Hernández, G. B., and Artés, F. (2010). UV-C doses to reduce pathogen and spoilage bacterial growth *in vitro* and in baby spinach. *Postharvest Biol. Technol.*, **56**, 223-231.
- FAO (2011). Global food losses and food waste – Extent, causes and prevention. Rome
- Incropera, F. P. and DeWitt, D. P. (2001). “Fundamentals of Heat and Mass Transfer (5th ed.)” Asia: Wiley.
- Japan Society of Thermophysical Properties (1990). “Thermophysical Properties Handbook.” Tokyo: Yokendo Ltd.
- Kim, J., Moreira, R., Huang, Y., and Castell-Perez, M. (2007). 3-D dose distributions for optimum radiation treatment planning of complex foods. *J. Food Eng.*, **79**, 312-321.
- Lammertyn, J., De Ketelaere, B., Marquenie, D., Molenberghs, G., and Nicolaï, B. M. (2003). Mixed models for multicategorical repeated response: modelling the time effect of physical treatments on strawberry sepal quality. *Postharvest Biol. Technol.*, **30**, 195-207.
- Manzocco, L., Da Pieve, S., Bertolini, A., Bartolomeoli, I., Maifreni, M., Vianello, A., and Nicoli, M. C. (2011). Surface decontamination of fresh-cut apple by UV-C light exposure: Effects on structure, colour and sensory properties. *Postharvest Biol. Technol.*, **61**, 165-171.
- Marquenie, D., Michiels, C. W., Van Impe, J. F., Schrevels, E., and Nicolaï, B. N. (2003). Pulsed white light in combination with UV-C and heat to reduce storage rot of strawberry. *Postharvest Biol. Technol.*, **28**, 455-461.
- Nigro, F., Ippolito, A., Lattanzio, V., Di Venere, D., and Salerno, M. (2000). Effect of ultraviolet-C light on postharvest decay of strawberry. *Plant Pathol.*, **82**, 29-37.
- Norton, T. and Sun, D. (2006). Computational fluid dynamics (CFD) - an effective and efficient design and analysis tool for the food industry: A review. *Trends Food Sci. Tech.*, **17**, 600-620.
- Pan, J., Vicente, A. R., Martínez, G. A., Chaves, A. R., and Civello, P. M. (2004). Combined use of UV-C irradiation and heat treatment to improve postharvest life of strawberry fruit. *J. Sci. Food Agr.*, **84**, 1831-1838.
- Scott, G. and Richardson, P. (1997). The application of computational fluid dynamics in the food industry. *Trends Food Sci. Tech.*, **8**, 119-124.
- Stevens, C., Wilson, C. L., Lu, J. Y., Khan, V. A., Chalutz, E., Droby, S., Kabwe, M. K., Haung, Z., Adeyeye, O., Pusey, L. P., Wisniewski M. E., and West, M. (1996). Plant hormesis induced by ultraviolet light-C for controlling postharvest diseases of tree fruits. *Crop Prot.*, **15**, 129-134.
- Tanaka, F., Verboven, P., Scheerlinck, N., Morita, K., Iwasaki, K., and Nicolaï, B. (2007). Investigation of far infrared radiation heating as an alternative technique for surface decontamination of strawberry. *J. Food Eng.*, **79**, 446-452.
- Trivittayasil, V., Nashiro, K., Tanaka, F., Hamanaka, D., and Uchino, T. (2015). Inactivation characteristics and modeling of mold spores by UV-C radiation based on irradiation dose. *Food Sci. Technol. Res.*, **21**, 365-370.
- Vicente, A. R., Pineda, C., Lemoine, L., Civello, P. M., Martinez, G. A., and Chaves, A. R. (2005). UV-C treatments reduce decay, retain quality and alleviate chilling injury in pepper. *Postharvest Biol. Technol.*, **35**, 69-78.