NUMERICAL SIMULATION OF THE INFLUENCE OF SOME GEOMETRIC PARAMETERS ON THE DECONTAMINATION QUALITY OF A NON-LAMBERTIAN TYPE DETECTOR, USING A UV-C LEDs MATRIX
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SIMULARE NUMERICĂ A INFLUENȚEI UNOR PARAMETRI GEOMETRICI ASUPRA CALITATII DECONTAMINARII UNUI RECEPTOR DE TIP NON-LAMBERTIAN, UTILIZAND O MATRICE DE LED-uri UV-C

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ABSTRACT
The ultraviolet (UV) irradiation has been studied and used in the recent decades as a mean to inactivate various potentially harmful microorganisms, being considered an effective treatment that could limit or even avoid the use of chemical disinfectants. Within the wavelength spectrum of UV radiation, the UV-C radiation wavelength ranging between 200 and 280 nm is considered lethal to most types of microorganisms. In this paper it was studied the variation of the distribution of radiation's intensity generated by a matrix of 25 UV-C LEDs (5 x 5), (assimilated to the LED panel above a stationary conveyor), on a spherical surface (assimilated to a berry) positioned in reprezentative locations below the matrix. A fruit located under the irradiation matrix receives the strongest radiation from the LED located at the smallest distance from it, but is influenced, as a result of the superposition principle, to a lesser extent by the other LEDs within the network. It has been found that for a too small distance between the matrix of LEDs and the conveyor, the radiation dose is uneven on the surface of fruit, and by increasing this distance a radiation distribution much more uniform is obtained, but at the expense of a decrease in its intensity and an increase in the time required for irradiation, implicitly leading to an increase in operating costs. In conclusion, for the most efficient operation of the equipment, a compromise solution must be chosen.

REZUMAT
Radiatia ultravioletă (UV) a fost studiată și utilizată în ultimele decenii ca mijloc de inactivare a diferitelor microorganisme potențial dăunătoare, fiind considerată un tratament eficient care ar putea limita sau chiar evita utilizarea dezinfectanților chimici. În spectrul radiației UV, lungimea de undă a radiației UV-C cuprinsă între 200 și 280 nm este considerată letală pentru majoritatea tipurilor de microorganisme. In aceasta lucrare a fost studiata variația distribuției intensității radiației generate de o matrice de 25 LED-uri UV-C (5 x 5), (asimilate unui panou LED pozitionat deasupra unui transportor in repaos), pe o suprafață sferică (asimilată unui fruct de pădure) poziționata în locații reprezentative sub matrice. Un fruct situat sub matricea de iradiere primește cea mai puternică radiație de la LED-ul situat la cea mai mică distanță de acesta, dar este influențat, ca urmare a principiului superpozitiei, într-o măsură mai mică de celelalte LED-uri din cadrul rețelei. S-a constatat că pentru o distanță prea mică între matricea LED-urilor și transportor, doza de radiație este neuniformă pe suprafața fructelor, iar prin creșterea acestei distanțe obținem într-adevăr o distribuție a radiației mult mai uniformă, dar cu prețul scăderii intensității acesteia și creșterii timpului necesar iradierii, conducând implicit la o creștere a costurilor de exploatare. In concluzie, pentru functionarea cat mai eficienta a echipamentului trebuie aleasa o solutie de compromis.

INTRODUCTION
The ultraviolet (UV) irradiation has been studied and used in the recent decades as a mean to inactivate various potentially harmful microorganisms, being considered an effective treatment that could limit or even avoid the use of chemical disinfectants (*Romero-Martínez et al., 2022*). Within the wavelength spectrum of UV radiation, the UV-C radiation wavelength ranging between 200 and 280 nm is considered lethal to most types of microorganisms, affecting the DNA replication of these microorganisms, causing breaks of molecular chemical bonds and inducing photochemical reactions that, ultimately, lead to their inactivation.

For this reason, the non-ionizing ultraviolet radiation UV-C is used as an alternative to chemical sterilization and microbial reduction in food products and has been approved for use as a disinfectant for surface treatment of food *(US-FDA, 2002*).

UV-C is already used successfully in various fields, such as medicine, ecology, postharvest technologies etc., alone (*Rodgers et al., 2023; Calle et al., 2023; Meneses-Espinosa et al., 2023; Ruetalo et al., 2022; Yemmireddy et al., 2022; Iturralde-García et al. 2022; Cruz Mendoza et al., 2022; Berruti et al., 2021; Sorică et al., 2021*), or in combination with other methods (e.g. the use of ozone) (*Sottani et al., 2023; Dogu-Baykut et al., 2022; Martínez de Alba et al., 2021; Frigerio et al., 2021; Gutiérrez et al., 2017*).

Within the food industry, ultraviolet radiation is mainly used for disinfecting surfaces and air, complementing the cleaning measures within production facilities and storage rooms, to avoid the spread of harmful microorganisms such a wide range of viral and bacterial pathogens. As a postharvest treatment of fresh produce, UV-C irradiation has been proven beneficial to reduce respiration rates, control rot development, and delay senescence and ripening in different whole or fresh-cut fruits and vegetables, such as apples, citrus, peaches, watermelon, grape berries, tomatoes, lettuce, baby spinach and mushrooms (*de Capdeville et al., 2002; Lamikanra et al., 2005; Allende et al., 2008; Artés-Hernández et al., 2010; Escalona et al., 2010; Jiang et al., 2010; Fava et al., 2011; Manzocco et al., 2011*). Furthermore, UV-C has also been shown to elicit a range of biochemical responses in fresh produce ranging from induction of antifungal enzymes to formation of phytoalexin compounds (*Guan et al., 2012*), elements which have been positively correlated with resistance against several pathogens and reduction of physiological disorders occurring during cold storage of fruits and vegetables (*Rivera-Pastrana et al., 2007*). Another advantage of applying UV-C is the capability to improve nutraceutical properties, due to an increase of bioactive compounds with antioxidant capacity.

UV-C is almost nonexistent in nature, because it is completely absorbed in the atmosphere. Artificial sources of UV-C light are produced, mainly, by the lamps of low pressure or high / medium pressure and, more recently, light emitting diodes - LEDs. Low pressure lamps produce, essentially, monochromatic light at a wavelength of 253.7 nm, very close to the peak of germicidal efficiency, respectively 264 nm. Medium pressure lamps produce a polychromatic light on a broader spectrum. UV-C LEDs emit monochromatic light at different wavelengths between 265 nm and 285 nm. Most effective and narrow targeted on the peak of germicidal wavelength seem to be the low pressure lamps and UV-C LEDs, both emitting, almost entirely, monochromatic radiation. Although the two technologies have gained interrest for its germicidal applications, there are some differencies that bring along various advantages and disadvantages for the use of one or another. Even if the low pressure lamps have high output power for germicidal radiation, they demonstrate several disadvantages such as the necessity of warming up, low energetic efficiency and relatively short lifetime. On the other hand, UV-C LEDs show several benefits regarding the traditional UV lamps such as less electric consumption, no necessity of a warming up period, longer lifetime, greater flexibility in the wavelengths of emission and greater possibilities for configuration within the working space, yet having a low output power, emitting in very narrow wavelengths, having low energy efficiency and high directionality (*Romero-Martínez et al., 2022*).

In order to estimate the technical conditions in which an equipment can apply a certain dose of UV-C, either in a design stage or when evaluating its performance, it is necessary to know the intensity of the radiation and the time of its application in different key points, representative for the working process of the respective equipment. This already implies the knowledge of the type, technical characteristics, dimensions and layout geometry of the UV-C generators within the working space, as well as their positioning in relation to the targeted points.

There are studies that aimed to develop or numerically simulate mathematical models designed for estimating the distribution of UV-C radiation's intensity in the vicinity of a radiation source, be it a linear or point source. The most important mathematical models developed for a linear UV-C radiation source are represented by the Keitz (*Keitz, 1971*), Modest (*Modest, 1993*) or Beggs (*Beggs et al., 2000*) models, which generate quite similar results both in the immediate vicinity of the radiation source and at the distance. For a point source of radiation, the model presented by Keitz is representative, based on the inverse square law of Lambert.

In this paper it is proposed to study, through numerical simulation, the variation of the distribution of radiation's intensity generated by a matrix of UV-C LEDs (assimilated to the LED panel above a stationary conveyor), on a spherical surface (assimilated to a berry) positioned in reprezentative locations below the matrix.

MATERIALS AND METHODS

Before studying the variation of the distribution of UV-C radiation's intensity on the surface of the berries, some simplifying hypothesis were made:

- The fruits are considered to have a perfectly spherical shape;
- All fruits are the same size;
- The advance of the fruits on the conveyor is carried out without any rolling movement;
- The fruit distribution is perfectly uniform over the entire surface of the conveyor.

In the first part of the study, a comparison was made between the radiation dose received by a fruit located in the most disadvantageous position, i.e. in one of the corners (fig. 1) and in the most advantageous position from this point of view, the one located in the center (fig. 2). To simplify the calculations, it is considered that the equipment consists of a matrix of only 25 LEDs (5 x 5), located at a distance "l" between them on the two axes and at a height "h" from the conveyor.

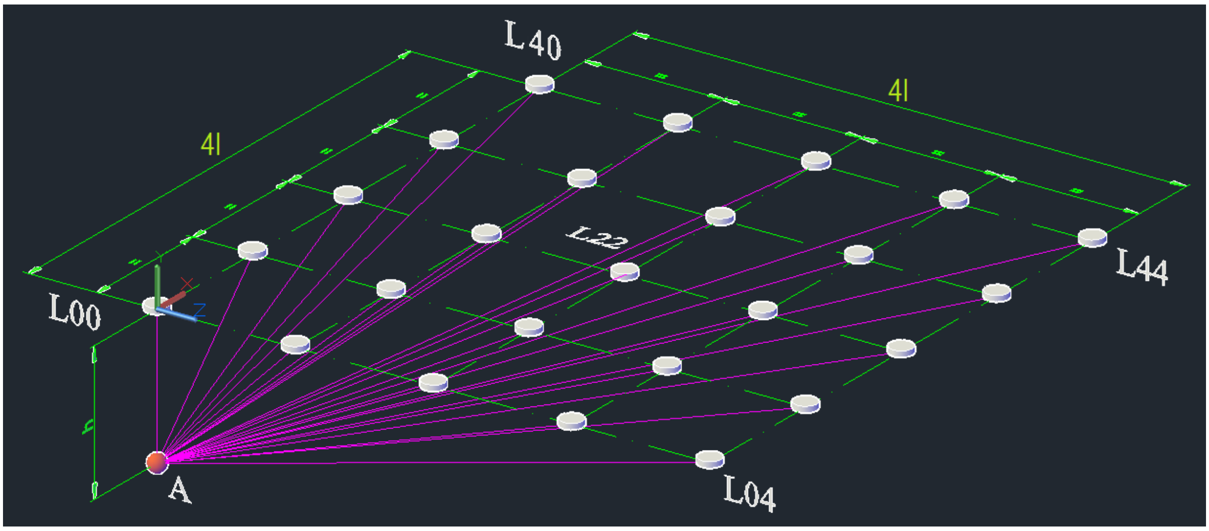


Fig. 1 - Visualization of the radiation reaching fruit "A", located below a corner of the LED array

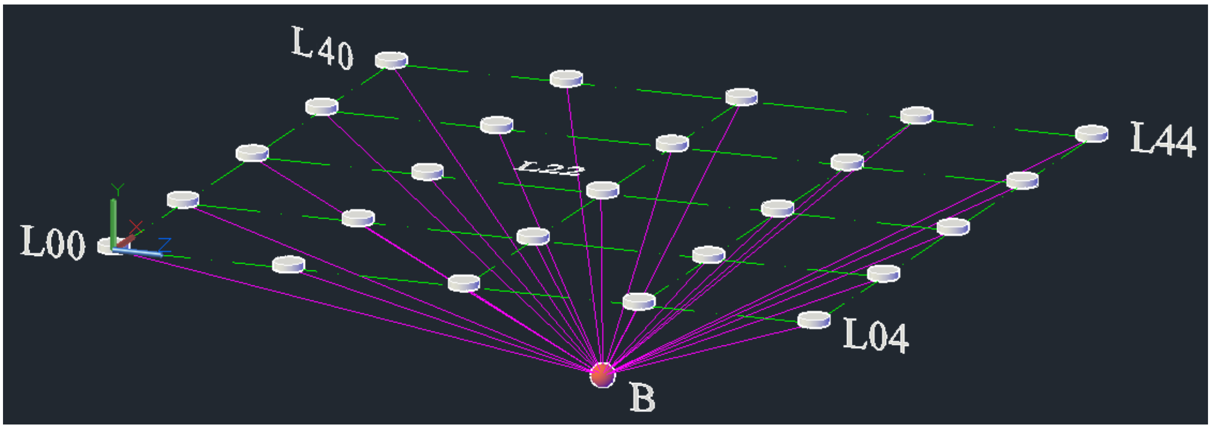


Fig. 2 - Visualization of the radiation reaching fruit "B", located below the center of the LED array

A fruit located under the irradiation matrix receives the strongest radiation from the LED located at the smallest distance from it, but is influenced, as a result of the superposition principle, to a lesser extent by the other LEDs within the network.

According to the inverse square law, the intensity of radiation "E" equals the incident luminous flux "Φ" divided by the area "S" (fig. 3) (the units of measure are adapted for the usual practice of UV-C radiation):

$$E = \frac{\emptyset}{S} = \frac{\omega \cdot I}{\omega \cdot r^2} = \frac{I}{r^2} \quad [W \cdot m^{-2}] \tag{1}$$

where: Φ is the incident luminous flux, [W];

S – the area receiving the incident luminous flux, [m²];

ω – the solid angle [sr];

I – the luminous intensity in all directions within a solid angle, [W];

r – the radius of a sphere with L as centre, [m].

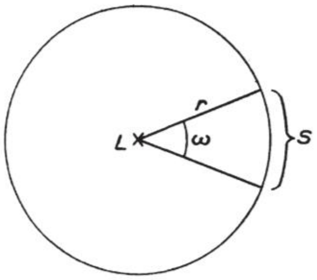


Fig. 3 - Derivation of the inverse square law (*Keitz, 1971*)

If it is imagined that the surface diminished in size to a mere point, it results that the illumination at a point in a plane perpendicular to the line joining the point and the source (the intensity of radiation "E") is equal to the luminous intensity of the source in the direction of the point, divided by the square of the distance between point and source (*Keitz, 1971*). This way the equation (1) becomes:

$$E = \frac{I}{d^2} \quad [W \cdot m^{-2}] \tag{2}$$

where: I – is the luminous intensity of the source in the direction of the point, [W];
d – is the distance between point and source, [m].

When the radiation from a source "L" falls at a point "P" on a plane "V" at an angle "α" to the normal at "P", the illumination of the plane "V" at point "P" obeys the Lambert's cosine law stating that the illumination at that point is directly proportional to the cosine of the angle "α" between the direction of incident radiation and normal to the plane in that point (fig. 4).

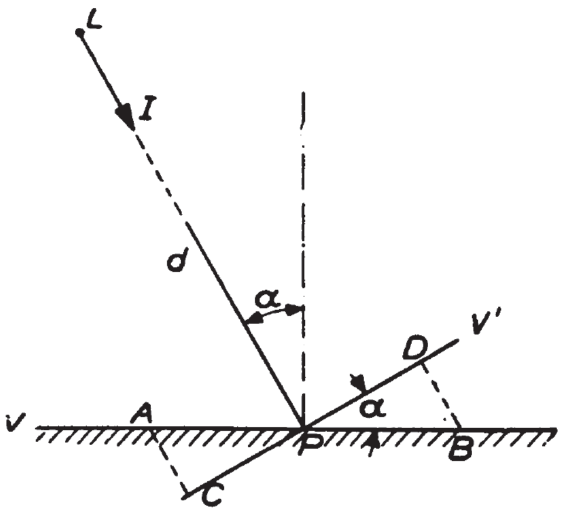


Fig. 4 - Cosine law for the illumination with oblique incidence (*Keitz, 1971*)

Using equation (2), it results:

$$E = E' \cdot \cos\alpha = \frac{I}{d^2} \cdot cos\alpha \quad [W \cdot m^{-2}] \tag{3}$$

where:

E' is the intensity of radiation at point "P" that is contained within the plane " V' " perpendicular to the line joining the point "P" and the source "L";

I and d have the significance previously described at equation (2);

α – the angle between the direction of incident radiation and normal to the plane in that point, [°].

Due to the fact that, from the initial simplifying hypothesis, the detector (the berry) is considered to has a perfectly spherical shape and not a planar surface (is a non-Lambertian detector), the cosine law does not apply to it. A fruit of radius "R" whose center is at a distance "h" from the radiation source is considered. The irradiated surface is the surface area of the spherical cap in figure 5.

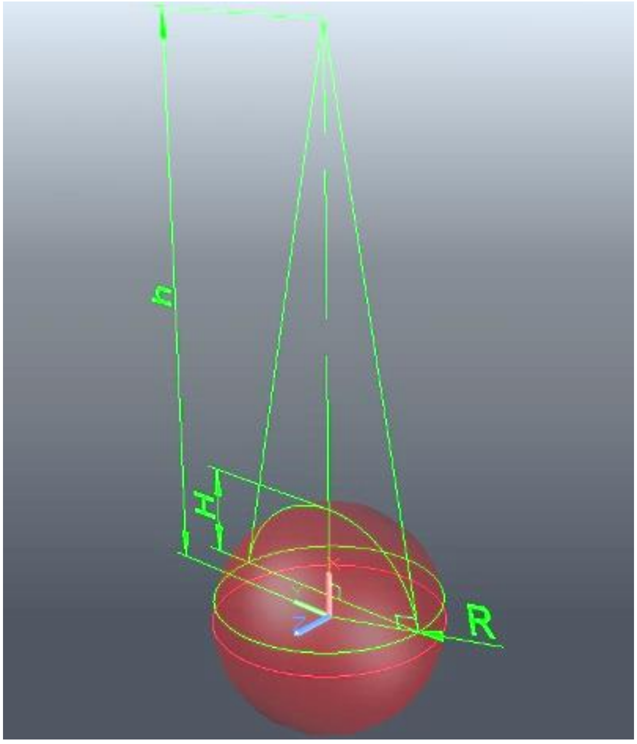


Fig. 5 - The elements that enter into the calculation of the surface area of the spherical cap

The area of the spherical cap is calculated using the relation:

$$A = 2 \cdot \pi \cdot R \cdot H \quad [m^2] \tag{4}$$

where: R is the radius of the fruit subjected to decontamination, [m];
H - the height of the spherical cap, [m].

Knowing that within the representation in figure 5, the two segments that join the radiation source and the surface of the fruit, symmetrical to the central vertical axis, are tangent to the respective surface in the two marginal points which define the chord that delimits the respective spherical cap, by expressing the half of the chord using the Pythagorean Theorem and the Theorem of the height in the right-angle triangles formed, followed by the equality of the two mathematical relations, is obtained the formula of the area depending on "h" and "R":

$$A = \frac{2 \cdot \pi \cdot R^2 (h - R)}{h} \quad [m^2] \tag{5}$$

Further, the dose of the absorbed radiation is defined as the intensity of radiation "E" multiplied by time "t":

$$D = E \cdot t \quad [W \cdot s \cdot m^{-2}] \tag{6}$$

where: E is the intensity of UV-C radiation within a certain point, [$W \cdot m^{-2}$];
t – the time that this radiation intensity is applied, [s].

Knowing that the dose of the absorbed radiation is directly proportional to the intensity of radiation "E', which is inversely proportional to the square of the distance from the source, it will be determined how important the radiation received from other LEDs besides the one located exactly above the fruit is. The fruit "A", respectively fruit "B", will simultaneously accumulate several doses of irradiation starting from the strongest, due to LED "L00", respectively LED "L22", to the weakest due to LED "L44", respectively LED "L00", "L04", "L40" and "L44".

The following aspects were followed:

- The variation of the influence of each LED in the matrix on the irradiation dose to which the fruit in position "*A*", respectively "*B*", is subjected;
- The influence of the variation of the distance "h" between the matrix of LEDs and the conveyor on the distribution density of UV-C radiation;
- The variation of the irradiated surface depending on the size of the fruit and its distance from the radiation source.

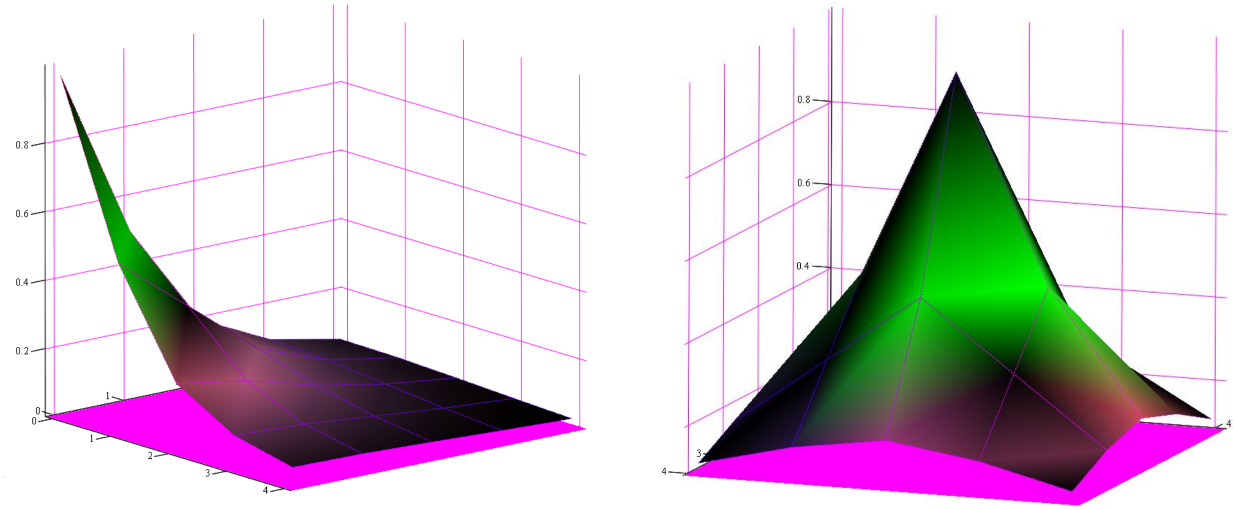
RESULTS

The inverse of the square of the distances between the radiation sources and the fruit "A", respectively fruit "B" is simply calculated from the formed triangles, using the Pythagorean theorem and the data can be visualized in the following type of matrix.

$$L_A := \begin{bmatrix} \frac{1}{h^2} & \frac{1}{(l^2+h^2)} & \frac{1}{(4l^2+h^2)} & \frac{1}{(9l^2+h^2)} & \frac{1}{(16l^2+h^2)} \\ \frac{1}{(l^2+h^2)} & \frac{1}{(2l^2+h^2)} & \frac{1}{(5l^2+h^2)} & \frac{1}{(10l^2+h^2)} & \frac{1}{(17l^2+h^2)} \\ \frac{1}{(4l^2+h^2)} & \frac{1}{(5l^2+h^2)} & \frac{1}{(8l^2+h^2)} & \frac{1}{(13l^2+h^2)} & \frac{1}{(20l^2+h^2)} \\ \frac{1}{(9l^2+h^2)} & \frac{1}{(10l^2+h^2)} & \frac{1}{(13l^2+h^2)} & \frac{1}{(18l^2+h^2)} & \frac{1}{(25l^2+h^2)} \\ \frac{1}{(16l^2+h^2)} & \frac{1}{(17l^2+h^2)} & \frac{1}{(20l^2+h^2)} & \frac{1}{(25l^2+h^2)} & \frac{1}{(32l^2+h^2)} \end{bmatrix}$$

Fig. 6 - The matrix containing the inverse of the squares of the distances between the radiation sources and the fruit "*A*"

The calculation and graphics were performed using MathCAD software. The graphic based on this matrix gives us information on the influence that each LED in the network has on the irradiation dose to which the fruit is subjected (fig.7). Being a qualitative reprezentation, the calculation was simplified further by choosing conveniently the radiation intensity "I", the distance between LEDs "l", the height of LEDs matrix "h" compared to the fruits and the time "t" how long the radiation intensity is applied. All these parameters were considered equal to one unit of each.



a) b)

Fig. 7 - The influence of each LED in the network on the irradiation dose to which the fruit is subjected: a) - in position "A"; b) - position "B"

From the graph (fig.7a) it can be seen that only the LEDs located in the immediate vicinity of "L00" significantly influence the level of radiation received by fruit "A", the LEDs located at a distance of "2l" have a influence of only 20% of the radiation due to "L00". From the graph in fig. 7b, it can be seen that the influence of the radiation received from the entire LED network on fruit B, located in the center, is more pronounced than in the first case. In order to study the influence of the distance "h" at which the LED matrix is located above the conveyor, on the uniformity of the radiation received by the fruits, a 2-fold reduction of the unit distance and then a 2-fold increase were taken into account. The resulting graphs are presented in fig. 8.

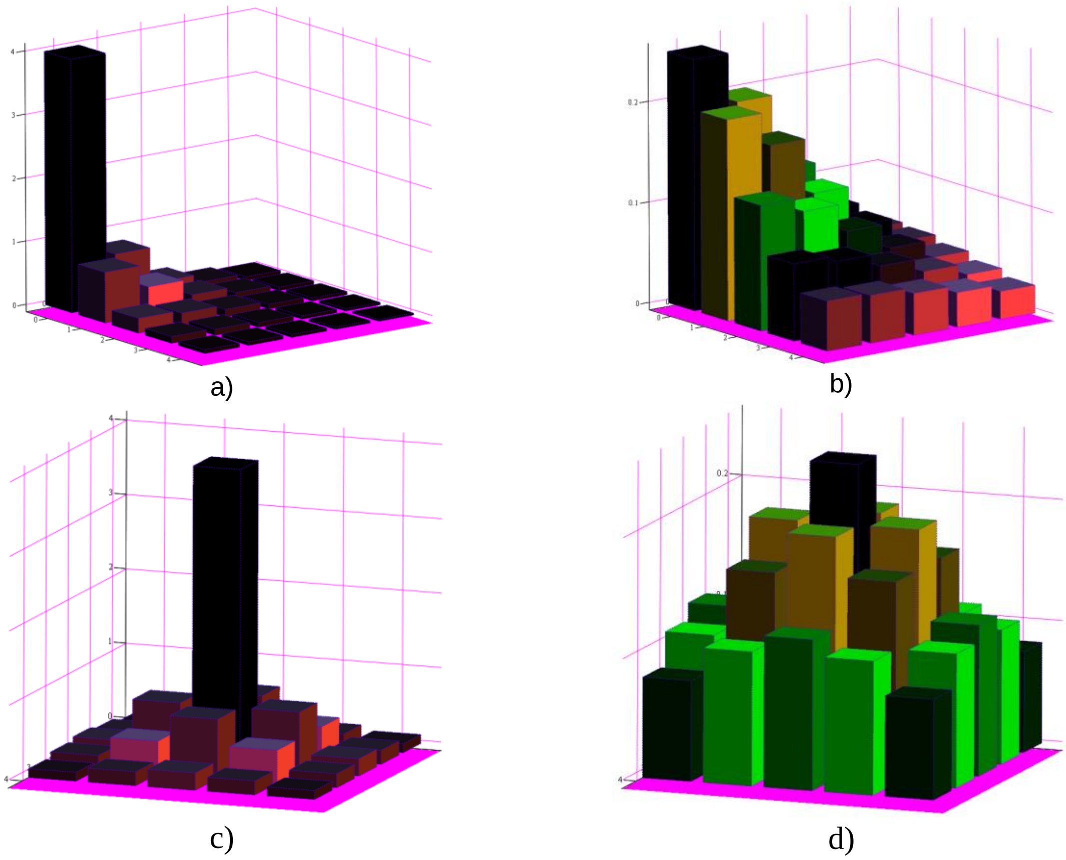


Fig. 8 - The influence of the variation of the distance “h” between the matrix of LEDs and the conveyor on the distribution density of UV-C radiation:
a) and c) – at the 2-fold reduction of the unit distance; b) and d) – at the 2-fold increase of the unit distance

From the graphs in fig. 8 it can be seen that the reduction of the distance "h" between the LED array and the conveyor leads to a reduction in the influence of the radiation coming from the adjacent LEDs, while an increase of this distance will lead to a much more uniform distribution of the radiation on the entire surface of the conveyor.

In the design stage of a fruit decontamination equipment using UV-C radiation, it must be taken into account that for a distance "h" that is too small, the radiation dose is uneven on the surface of fruit, and by increasing this distance a radiation distribution much more uniform is obtained, but at the expense of a decrease in its intensity and an increase in the time required for irradiation, implicitly leading to an increase in operating costs. In conclusion, for the most efficient operation of the equipment, a compromise solution must be chosen.

If the area A is considered a function of two variables, f(R, h), its variation can be represented graphically in a 3-dimensional space, using the MathCAD program, obtaining the graph shown in figure 9.

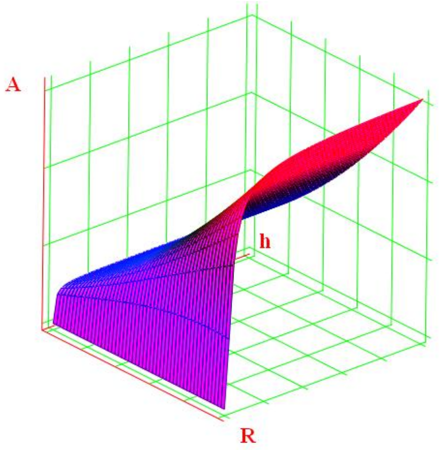


Fig. 9 - The variation of the decontaminated area of the fruit depending on its radius and the distance from UV-C source

For this study the variation of radius "R" was considered between 4 and 10 mm (blueberry) and the distance "h" was choosen between " R " and 500 mm. At the limit, the surface subjected to decontamination varied between 0 and $2\pi R^2$ (respectively half the surface of the sphere), as the distance "h" from the LEDs matrix, varies between "R" and "∞".

$$\lim_{h \to R} \frac{2 \cdot \pi \cdot R^2 \cdot (h-R)}{h} \to 0 \tag{7}$$

$$\lim_{h \to \infty} \frac{2 \cdot \pi \cdot R^2 \cdot (h-R)}{h} \to 2 \cdot \pi \cdot R^2 \tag{8}$$

A conclusion that emerges from the previously presented is that increasing the height "h" will cause an increase in the irradiated surface, but a decrease in the intensity of the incident radiation.

CONCLUSIONS

The paper has studied the variation of the distribution of radiation's intensity generated by a matrix of 25 UV-C LEDs (5 x 5), (assimilated to the LED panel above a stationary conveyor), on a spherical surface (assimilated to a berry) positioned in reprezentative locations below the matrix, respectively in the most disadvantageous positions and in the most advantageous ones.

The following conclusions were identified:

- only the LEDs located in the immediate vicinity of the corner significantly influence the level of radiation received by fruit "A". Also it can be seen that the influence of the radiation received from the entire LED network on fruit „B", located in the center, is more pronounced than in the first case.

- the reduction of the distance "h" between the LED array and the conveyor leads to a reduction in the influence of the radiation coming from the adjacent LEDs, while an increase of this distance will lead to a much more uniform distribution of the radiation on the entire surface of the conveyor.

- for a distance " h " that is too small, the radiation dose is uneven on the surface of fruit, and by increasing this distance a radiation distribution much more uniform is obtained, but at the expense of a decrease in its intensity and an increase in the time required for irradiation, implicitly leading to an increase in operating costs.

In conclusion, for the most efficient operation of the equipment, a compromise solution must be chosen.

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