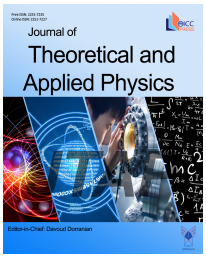

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Extending agricultural product shelf life and enhancing microbial control with UV-C radiation

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Original Research

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Abstract:

This study explores the impact of UV-C radiation on microbial contamination and the shelf life of agricultural products. UV-C radiation, known for its efficient absorption by nucleic acid bases, induces thymine dimer formation in microorganisms like Staphylococcus aureus, Pseudomonas aeruginosa, and Escherichia coli. It is observed that, the quantity of thymine dimers increases with shorter distances and longer exposure times to the UV-C lamp, significantly affecting microbial viability. Moreover, the optimal conditions for maximum thymine dimer formation were seen at closer distances (5 cm) and longer exposure times (120 seconds), underscoring the need to balance exposure duration to prevent DNA repair mechanisms from reducing UV-C treatment effectiveness. Furthermore, UV-C treatment effectively prolongs the shelf life of agricultural products such as tomatoes, plums, and cherry tomatoes by delaying decay and spoilage. Treatment durations of 40 to 60 seconds were found most effective in extending storage durations, with tomatoes extending from 1 week to up to 3 weeks, and cherry tomatoes up to 2 months. The optimal parameters identified (such as a 10 cm distance and 40 seconds exposure time) offer practical guidelines for enhancing product safety and reducing bacterial contamination in food processing and storage facilities.

Keywords: UV-C radiation; Microbial contamination; Shelf life of foods and agricultural products

1. Introduction

Nowadays, food preservation faces significant challenges, primarily due to microbial contamination that reduces food quality and shortens shelf life. Traditional chemical methods used to combat these issues often pose health risks and are becoming less effective due to rising antibiotic resistance. Hence, the need for alternative, safer food preservation techniques is critical, as current methods may not be suitable for ensuring long-term food safety and quality [1]. Promising non-chemical disinfection techniques, such as non-thermal plasma, thermal treatment, anti-microbially embedded filters, ultraviolet (UV) light, and photocatalysis, are being explored to address food preservation challenges [2, 3]. UV germicidal irradiation (UVGI) [4] stands out due to its high efficiency and affordability, making it ideal for disinfecting air, water, and surfaces. UVGI is particularly effective in enhancing the safety of fresh produce throughout the food production chain by disrupting the RNA of viruses, including coronaviruses [5]. UV disinfection, specifically using UV-C radiation, is a physical method that inactivates microorganisms by damaging their DNA and RNA. UV-C light, especially at a 254 nm wavelength, shows the strongest germicidal effect by inducing the formation of thymine-thymine dimers in DNA, preventing cell replication. However, the effectiveness of UV-C irradiation depends on factors like the distance from the light source and the surface characteristics of the items being treated [4, 5].

Abdul Karim Shah [6] highlighted UV-C as a key non-thermal technique for fruit juice processing, demonstrating

that it can produce microbiologically safe products while maintaining the quality of the juices with minimal negative impact. Moreover, Delorme et al. [7] introduced UV-C as a promising technology for preserving the quality and safety of milk and dairy foods. Their research demonstrated that UV-C radiation effectively inactivates pathogenic and spoilage microorganisms in milk and dairy products by causing DNA lesions and/or damaging cellular enzyme activity and cytoplasmic membrane integrity. Besides, they highlighted that the efficiency of UV-C treatment depends on various factors, including process parameters (exposure time, UV dose, wavelength, and UV light source), product characteristics (chemical composition, viscosity, turbidity, opacity, and surface roughness), equipment design (conformation and geometry), and microorganism attributes (species, strain, initial count, growth phase, and recovery conditions) [7]. A. K. Banas et al. [8] studied the DNA damage produced under UV with a special focus on the pyrimidine dimers formed between the neighboring pyrimidines in a DNA strand. Moreover, they have briefly discussed Photolyase enzymes properties, structure, specificity and action mechanism. Furthermore, the main gaps in human knowledge on the functioning of light repair in plant organelles, its regulation and its interaction between different DNA repair systems in plants are highlighted [8].

A. Nagpal et al. [9] clarified that bacteria inactivation by UV radiation is caused due to the formation of thymine dimers that inhibit DNA replication. In their experiments absorption, fluorescence, synchronous fluorescence, and Raman spectra of nonirradiated and UV-irradiated thymine solutions were recorded in order to detect thymine dimer formation. The thymine dimer formation, as a function of irradiation dose, was determined by Raman spectroscopy. Using synchronous fluorescence spectrum, the formation of a mutagenic $(6-4)$ photoproduct was identified. Finally, a fast method for determining, in situ, the reaction mechanism and final photoproducts formed as a function of UV irradiation dose was provided [9].

The UV-C radiation inactivation of *Escherichia coli* (*E. coli*) and *Listeria monocytogenes* (*L. monocytogenes*) on the surface of different fruits was studied by Adhikari et al. [10]. They exposed bacteria contaminated fruit surfaces with UV-C doses up to 11.9 kJ/m^2 at 23 °C. Moreover, they determined fruit surface roughness, contact angle, and surface energy and their correlation with UV-C inactivation kinetics. Their findings indicate that UV-C light can effectively reduce *E. coli* and *L. monocytogenes* populations on fruit and berry surfaces. However, surface characteristics influence the efficacy of UV-C radiation [10]. In another experimental work, Adhikari et al. [11] evaluated the potential of using UV-C treatment in reducing the microbial population in agricultural water. Waters with turbidity levels ranging from 10.93 to 23.32 Nephelometric Turbidity Units (NTU) were prepared by mixing pond and well water. They inoculated water with *E. coli* and treated it with UV-C radiation (20–60 mJ/cm^2). It was reported that a significant reduction of *E. coli* levels occurs in the water samples after UV-C treatment [11].

Manzocco et al. [12] studied the effectiveness of UV-C radiation treatments on the microbial load and quality of fresh-cut pineapple sticks. They found that pineapple sticks exposed to 200 J/m^2 UV-C radiation, packaged in conventional trays, and stored at 6 °C for up to 15 days exhibited slower yeast and lactic acid bacteria growth. In UV-C treated samples, microbial counts were generally 2 log cycles lower than those in the untreated sticks. Moreover, UV-C radiation did not alter the color of the pineapple sticks and even increased consumer preference [12].

A comparison between the inactivation efficacies of low-pressure mercury lamps and UVC LEDs for *E. coli* on lettuce leaves and *L. monocytogenes* on apple skin was performed by Green et al. [13]. It was shown that UVC LEDs at 277 nm have comparable germicidal efficacy to low pressure mercury lamps against the foodborne pathogens *E. coli* and *Listeria monocytogenes* on lettuce leaves and apple skin, respectively, while both light sources achieve log reductions similar to an aqueous sodium hypochlorite wash. Overall these results indicate that UVC is an alternative effective and sustainable method of disinfecting apples and lettuce in an industrial setting, reducing or eliminating the dependence on aqueous sanitizers. In addition, it was observed that use of UVC light for disinfection represents a possible dry means to augment or replace existing batch-wash disinfection systems for fresh produce [13].

In this work, the effects of UV-C radiation on both microbial contamination and the shelf life of agricultural products are studied. It experimentally examines how UV radiation impacts thymine dimer formation in diverse microorganisms, including *Staphylococcus*, *Pseudomonas aeruginosa*, and *Escherichia coli*. The research details the physical characteristics of the UV-C lamp used and the experimental methods employed, exploring how variations in UV radiation treatment times and distances influence thymine dimer formation in these microorganisms. Furthermore, the study assesses how UV radiation affects the storage longevity of various agricultural crops, such as plums, tomatoes, and cherry tomatoes.

2. Materials and methods

This study experimentally examines the effects of ultraviolet radiation on thymine dimer formation in various microorganisms, including *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Escherichia coli*. Initially, the physical characteristics of the UV-C lamp used and the experimental testing methods are described. Subsequently, the impact of different UV radiation treatment times and distances on thymine dimer formation in these microorganisms is investigated. In addition, the effects of UV radiation on the storage time of various agricultural crops, including plums, tomatoes, and cherry tomatoes are examined.

2.1 UV radiation source characteristics and experimental set-up

This UV-C lamp, manufactured by OSRAM Company, contains mercury in the form of small mobile parts within the bulb. The UV-C lamp is ozone-free and does not produce any ozone gas when in operation. Table 1 presents the technical and appearance specifications of the UV-C lamp. A

Table 1. OSRAM UV-C lamp properties.

Length	25.4 cm
Diameter	3.2 cm
Useful life	8000 h
The intensity of the passing current	0.05 A
Input voltage	230 V
UV radiation wavelength	254 nm (UV-C)
Operating frequency	50 to 60 Hz
Power	6 W
Radiant power	1.7 W

rectangular cube measuring 50 cm in length, 30 cm in width, and 30 cm in height is used as the experimental environment (Figure 1), with the lamp positioned on the upper surface of this rectangular cube.

To provide a more detailed perspective on the experiments conducted, the physical characteristics of the UV lamp were measured and are presented in Figure 2. Figure 2 (a) illustrates the variation of UV radiation intensity at different distances from the lamp. The results indicate that the light intensity decreases inversely with the square of the distance from the lamp. The maximum intensity is observed at the point closest to the lamp and its central areas. Consequently, the effects of this reduction in intensity can be used to determine the time required for bacterial inactivation in the experiments. Additionally, the temporal variations in the number of photons are presented in Figure 2 (b). The intensity values for different distances are obtained from Figure 2 (a). According to Figure 2 (b), the number of photons increases linearly with UV exposure time. For a distance of 5 cm, approximately 4.5×10^{17} photons are formed in 120 seconds, with the number of photons decreasing at greater distances. According to the relation of quantized photon energy, $E = nh\nu$, where n is the number of photons, h is Planck's constant, and ν is the emitted light frequency, the number of photons directly correlates with the energy of the emitted light. Thus, at higher intensities, due to the higher energy of photons, the slope of the increase in the number of photons is steeper. Conversely, at lower intensities, the number of photons is smaller, resulting in a gentler slope. As the distance increases, the germicidal property of the radiation decreases because fewer photons are formed, leading to less thymine dimer formation and reduced bacterial inactivation.

2.2 Classification of UV-treated microorganisms

• *Staphylococcus aureus*

Staphylococcus aureus is the most common species of *Staphylococcus* responsible for various infections. This gram-positive bacterium thrives at temperatures between 25 to 39 °C, with an optimal pH range of 7 to 7.5. It is resistant to dry environments, can grow without oxygen on standard culture media, is metabolically active, ferments many sugars, and produces colorful pigments.

• *Pseudomonas aeruginosa*

Pseudomonas aeruginosa is a type of bacteria commonly found in soil and water environments. It is the species most frequently causing infections in humans, leading to conditions such as blood infections, pneumonia, and post-surgical infections.

• *Escherichia coli* (*E. coli*)

Escherichia coli belongs to the Enterobacteriaceae family and is a gram-negative bacterium capable of fermenting glucose and producing gas. Widely present in the environment, *E. coli* is used as an indicator of fecal contamination

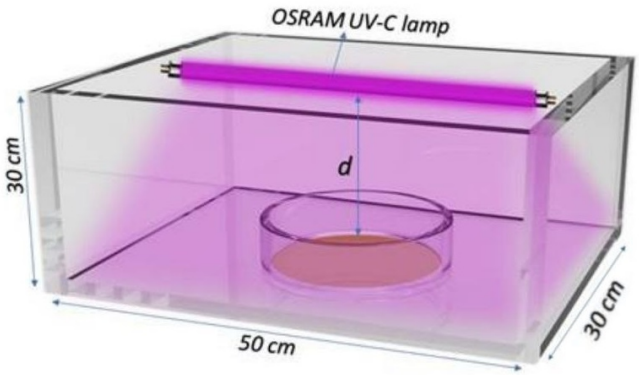

Figure 1. Schematic representation of the experimental setup.

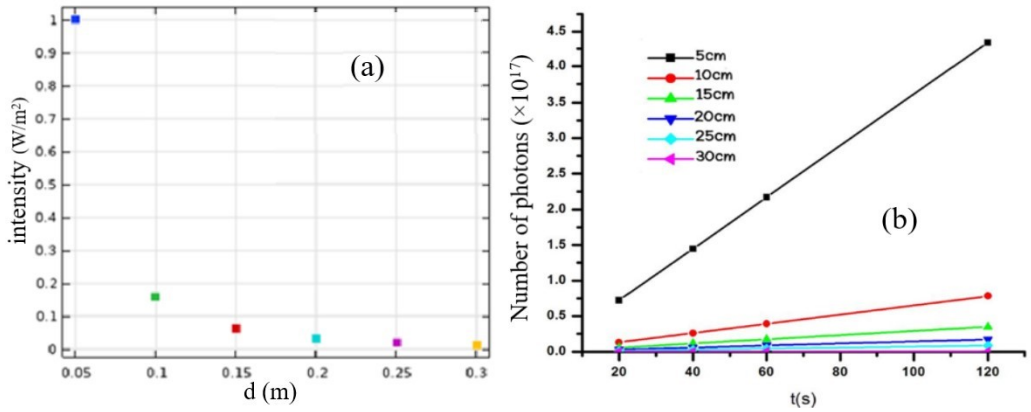

Figure 2. (a) Variation of the UV lamp radiation intensity as a function of distance from the lamp, (b) Number of UV photons as a function of exposure time at different distances from the lamp.

to assess water safety and quality. While most *E. coli* strains are harmless, some pathogenic strains can cause diseases like watery and bloody diarrhea, urinary tract infections, meningitis, and sepsis, potentially leading to death. *E. coli* is responsible for waterborne outbreaks in both developing and industrialized countries.

2.3 Preparation of culture medium and microorganism samples

The culture medium used was nutrient agar (CONDA, Co, Spain). Table 2 lists the components of this medium per liter. To prepare the medium, 40 grams of nutrient agar powder were dissolved in 1000 mL of distilled water and autoclaved at 120 °C for 15 minutes. After cooling to 45 − 50 °C, the medium was poured into sterile 6 cm Petri dishes. Fresh cultures of microorganisms (*Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *E. coli*) were prepared by inoculating the nutrient agar medium with a laboratory loop. After incubating for 24 hours, each culture was diluted to a half McFarland concentration (a level that allows for countable colonies) and further diluted as needed. Subsequently, 100 µL of each diluted culture was inoculated onto the previously prepared Petri dishes using the pour plate method.

2.4 UV treatment experiments

An untreated Petri dish was used as the control sample. Other Petri dishes were subjected to UV-C lamp treatment with varying conditions. Initially, the UV lamp was positioned 20 cm from the Petri dishes, and they were exposed for 60 and 120 seconds. The distance was then reduced to 10 cm, with exposure times of 30, 40, and 60 seconds applied. In a separate set of experiments, UV treatment was kept constant at 30 seconds while testing distances of 5 cm and 15 cm. Table 3 summarizes the UV treatment conditions and their results for different durations and distances. After treatment, both control and UV-treated Petri dishes were incubated. Besides, this study evaluates how UV-C treatment at various exposure times affects the shelf life of agricultural products like plums, tomatoes, and cherry tomatoes.

3. Results and discussion

This work focuses on the effectiveness of UV-C radiation treatment in reducing microbial contamination from various bacteria species, including *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *E. coli*. DNA, a fundamental structural component of microorganisms, plays a crucial role in biological systems, containing four nucleotides: Adenine (A), Thymine (T), Guanine (G), and Cytosine (C) [14]. UV radiation, both long and short wavelengths, can damage DNA in distinct ways. Shorter wavelength UV-B and UV-C radiation directly induce pyrimidine dimerization, impeding DNA replication and potentially causing mutations during imperfect repair processes. In contrast, longer wavelength UV-A radiation typically induces mutations via Reactive Oxygen Species (ROS) rather than direct DNA damage. UV-C radiation is particularly effective at damaging DNA due to its strong absorption by nucleic acid bases (purines and pyrimidines), leading to the formation of excited-state species that cause DNA lesions, ultimately resulting in cell death or mutation [15].

Pyrimidine dimers, such as those involving thymine bases, are molecular lesions formed through photochemical reactions in DNA [16, 17], and are closely associated with direct DNA damage. Besides, this work evaluates the impact of UV-C radiation on samples of *Staphylococcus*, *Pseu-*

Table 2. The compounds of culture medium.

Ingredient	Amount
NUTRIENT AGAR Powder	40 gr
Distilled water	1000 mL

Table 3. Arrangement of experiments for different UV treatment time and UV lamp and petri-dish distance.

Order	UV lamp and petri dish distance (cm)	UV irradiation time (s)	10^7LogCFU/mL
1 (control)	0	0	7
2	5	30	0
3	10	30	1
4	10	40	0.2
5	10	60	0
6	15	30	0
7	20	60	0.5
8	20	120	0

domonas aeruginosa, and *E. coli*, presenting findings on thymine dimer formation. Firstly, it is explored how varying distances from the UV-C lamp and treatment durations affect the quantity of thymine dimers formed. Furthermore, the effects of UV-C radiation on various agricultural products are examined. Each UV photon typically induces the formation of approximately two thymine dimers, and the percentage of pyrimidine dimers containing thymine serves as a measure of DNA damage severity, prioritizing the quantification of thymine dimers due to their prevalence in pyrimidine dimers.

3.1 The effects of UV exposure time duration and distance from UV lamp on the number of thymine dimer

Table 3 shows the average number of bacterial colonies (measured as 10^7 LogCFU/mL) for various UV exposure times and distances from the UV lamp. After 24 hours, the specimens were removed from the incubator for analysis. It was observed that increasing the distance from the UV lamp led to a decrease in the number of bacterial colonies, while increasing the exposure time also reduced the colony count. This trend is attributed to the higher UV intensity at greater exposure times and the lower intensity at greater distances from the UV lamp.

According to $E = nh\nu$, the number of photons is directly proportional to the energy of the emitted light. Higher intensities result in steeper changes in photon numbers due to increased energy emission, whereas lower intensities yield more gradual changes. As distance from the UV-C lamp increases, the antimicrobial effectiveness of UV radiation diminishes, resulting in fewer breaks in thymine bonds due to reduced photon numbers. Figure 3 illustrates the average number of thymine dimers formed in DNA. UV light, with an energy requirement of 4.88 eV to form a photon and 2.79 eV to create a thymine dimer [18], induces approximately two thymine dimers per photon. While each DNA molecule varies in its number of thymine dimers, the focus here is on the percentage of pyrimidine dimers containing thymine, emphasizing the prevalence of thymine dimers [19].

In Figure 3 (a), changes in thymine dimer counts across varying distances from the UV-C lamp and treatment times were analyzed. Thymine dimer counts decrease with greater distance from the lamp, with treatment times ranging from 20 seconds to 120 seconds. The maximum count, 3.5×10^4, occurs at 5 cm distance over 120 seconds. Distance proves crucial in thymine dimer formation, with longer UV treatment times generally resulting in higher dimer production,

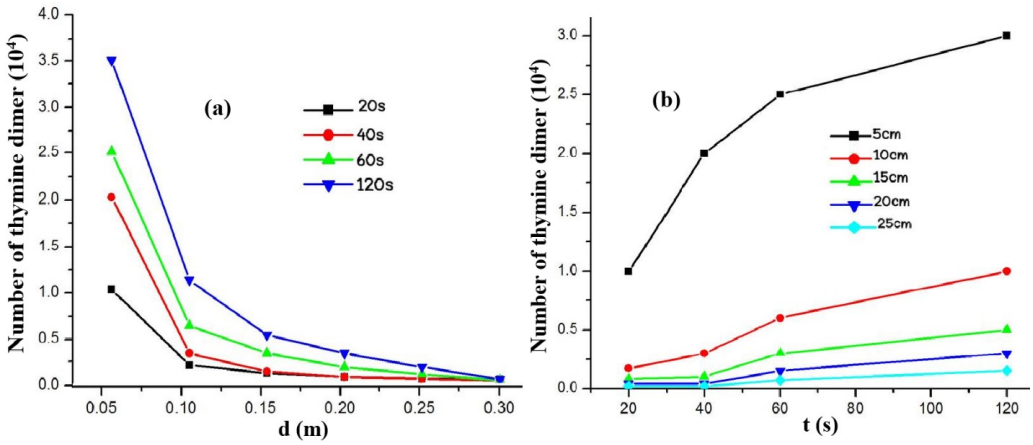

Figure 3. (a) Variation of number of thymine dimers changes versus distance from UV-C lamp for different treatment times. (b) Variation of number of thymine dimers changes versus the treatment time for different distances from UV-C lamp.

albeit excessively long exposures can diminish thymine dimer counts as DNA begins repairing dimers [19]. Figure 3 (b) examines temporal variations in thymine dimer counts across distances from 5 cm to 25 cm from the UV-C lamp. It shows an increase in thymine dimers over time, indicating greater DNA damage and subsequent disinfection. It must be noted that, at a 5 cm distance, thymine dimer counts rise from 1×10^4 to 3×10^4 in 120 seconds, marking this distance as most effective for thymine dimer production. At longer distances, thymine dimer counts decrease, signifying reduced DNA absorption of UV energy.
It is worthy to mention that, the results underscore UV-C treatment as highly effective for reducing and eliminating microorganisms. However, prolonged UV-C exposure can reverse thymine dimer destruction, making extended treatments unsuitable. Optimal distances and durations were identified through experiments on various microorganisms, highlighting 10 cm as the optimal distance and 40 seconds as the ideal duration, achieving a 90% reduction in colony growth. Given the significant variations in thymine dimer response to intensity, time, and distance, finding the optimal irradiation time can notably conserve energy in sectors employing UV radiation for disinfection. This technique not only enhances food and agricultural product safety by reducing bacteria but also potentially boosts agricultural exports.

3.2 The effect of UV lamp on some agricultural products

This study examines the impact of UV-C treatment at various exposure durations on the shelf life of agricultural products such as plums, tomatoes, and cherry tomatoes. The findings highlight UV-C treatment as pivotal in extending product shelf life. For instance, tomatoes have seen their shelf life increase from 1 week to 3 weeks, and cherry tomatoes have even extended to 2 months with relatively short UV-C exposure periods. Importantly, UV-C radiation does not alter the sensory qualities of food, maintaining texture, color, and aroma. The ease of application, cost-effectiveness, rapid treatment duration, and absence of harmful chemicals enhance the potential for international agricultural product exports due to prolonged shelf life. The qualitative attributes of fruits, including texture, color, and aroma, significantly influence consumer acceptance. Therefore, this study examines how UV radiation affects the storage duration of plums, tomatoes, and cherry tomatoes. Initial evaluations on the first day and immediately post-UV treatment showed no discernible differences in qualitative characteristics compared to untreated control samples. Figures 4, 5, and 6 show changes in UV-treated and untreated samples of plums, tomatoes, and cherry tomatoes over several days at room temperature. Control samples deteriorated noticeably, whereas increased UV treatment durations significantly prolonged the lifespan of these fruit samples. In addition, UV treatments lasting 40 to 60 seconds positively impact fruit storage durations.

4. Conclusion

In this work, the effects of UV-C radiation on microbial contamination and agricultural product shelf life are studied. It was found that, UV-C radiation, particularly effective due to its strong absorption by nucleic acid bases, induces thymine dimer formation in microorganisms such as *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Escherichia coli*. It was shown that the quantity of thymine dimers increases with shorter distances and longer exposure times to the UV-C lamp, crucially impacting microbial viability. As seen, the optimal conditions for maximum thymine dimer

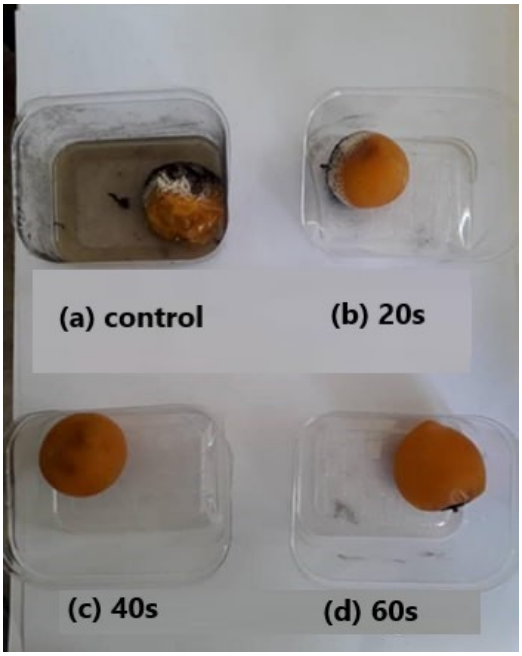

Figure 4. Changes in untreated and different treatment time UV treated samples of plums fruit after 17 days at room temperature: (a) control sample (without UV treatment) (b) 20 seconds UV treatment (c) 40 seconds UV treatment (d) 60 seconds UV treatment.

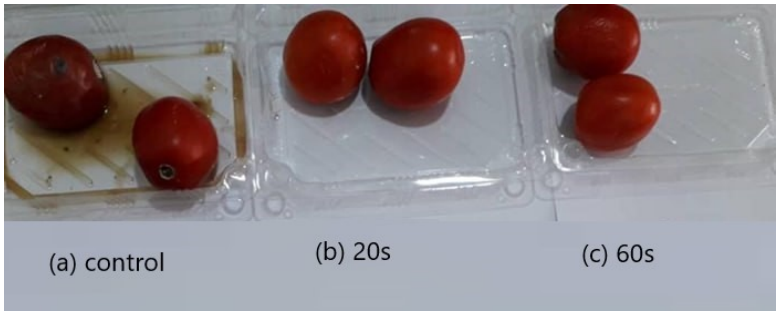

Figure 5. Depicts the changes observed in untreated and UV-treated tomato fruit samples after 10 days at room temperature: (a) Control sample (without UV treatment), (b) 20 seconds UV treatment, (c) 60 seconds UV treatment.

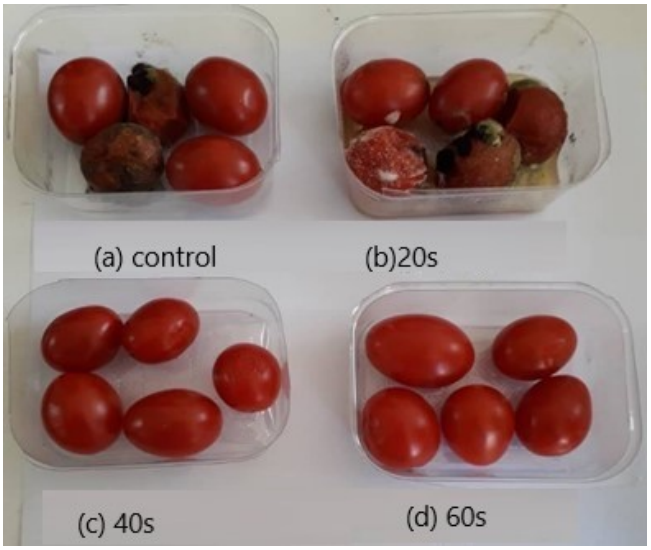

Figure 6. Changes in untreated and different treatment time UV treated samples of cherry tomatoes fruit after 30 days at room temperature: (a) Control sample (without UV treatment) (b) 20 seconds UV treatment (c) 40 seconds UV treatment (d) 60 seconds UV treatment.

formation were identified at closer distances (5 cm) and longer exposure times (120 seconds), highlighting the importance of balancing exposure duration to prevent DNA repair mechanisms from diminishing the effectiveness of UV-C treatment. Besides, the UV-C treatment significantly extends the shelf life of agricultural products like tomatoes, plums, and cherry tomatoes by delaying decay and spoilage. The treatment duration of 40 to 60 seconds proved most effective in prolonging the storage duration of these fruits, with tomatoes showing an extension from 1 week to up to 3 weeks and cherry tomatoes even extending up to 2 months. Importantly, UV-C treatment does not compromise the sensory qualities of these fruits, preserving their texture, color, and aroma, which are critical factors influencing consumer acceptance and marketability. Furthermore, the findings underscore UV-C radiation as a highly efficient method for microbial disinfection and extending the shelf life of agricultural products. The optimal parameters identified in this study (such as a 10 cm distance and 40 seconds exposure time) can guide practical applications in food processing and storage facilities to enhance product safety and reduce bacterial contamination. This study provides valuable insights into the application of UV-C radiation in both microbial disinfection and agricultural product preservation, highlighting its potential to improve food safety and extend shelf life, thereby benefiting both consumers and producers in the agricultural sector.

Authors contributions

All authors have made substantial contributions to the intellectual content, conception, and design of this work, as well as to the analysis and interpretation of the data (where applicable) and the writing of the manuscript.

Availability of data and materials

The data that support the findings of this study, including detailed experimental results on the effects of UV-C radiation on microbial contamination and the shelf life extension of agricultural products, are available from the corresponding author upon reasonable request. These data include measurements of thymine dimer formation, microbial viability assessments, and the specific conditions under which UV-C treatment was applied to tomatoes, plums, and cherry tomatoes.

The data have been made available in accordance with the policies of the Journal of Theoretical and Applied Physics to ensure transparency and reproducibility of the research.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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