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Research Article

Surface Disinfection and Food Safety Enhancement in Pistachios Through Ultraviolet Light Application

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Abstract: Pistachios are prone to contamination by soilborne and foodborne microorganisms after harvest, affecting their safety and quality. Due to unfavorable alterations in the product's physical and sensory qualities, several processing methods to lessen the microbial load on pistachios have not been reported as successful or practicable. This study evaluates the impact of ultraviolet-C (UV-C) light treatment on pistachios' physical, chemical, microbiological, and sensory properties. UV-C treatments were applied at 900, 1,800, and 2,700 seconds, with a light intensity of 0.044 W/cm^2, corresponding to doses of 39.6, 79.2, and 118.8 J/cm^2, respectively. Results showed that increasing UV-C dose led to a significant increase in total fat content and peroxide value, total antioxidant activity, *L** and *b** total phenolic substance content, a significant decrease in total chlorophyll content, *a** with no significant change in titratable acidity ($P \leq 0.05$). The decrease in total mesophilic aerobic bacteria, total mold and yeast, total *Salmonellae* and total coliform counts were 3.10, 3.38, 3.2 and 2.97 log cfu/g, respectively ($P \leq 0.05$). Sensory evaluations indicated that UV-C-treated samples, particularly those at 79.2 and 118.8 J/cm^2, received higher scores than control samples ($P \leq 0.05$). The concentrations of the major fatty acids, oleic, butyric, linolenic, and palmitic acids, showed fluctuations with the applied energy. These findings demonstrate that UV-C light treatment effectively inactivates microorganisms while enhancing bioactive compounds and maintaining product quality.

***Keywords*:** pistachios, UV-C, surface disinfection, microbial inactivation, sensory properties

1. Introduction

Pistachios (*Pistacia vera* L.), which have Central Asian origins, were brought to North and South America in 1957. Growing in areas between the 30° and 45° parallels worldwide, this hardy shrub can withstand drought and salt [1]. While the United States, Iran, China, Syria, and Greece are the main producers of pistachios worldwide, the Southeastern Anatolia Region of Turkey is a major growing region [2, 3]. Because of their high protein content, good fats, vitamins, and minerals, pistachios are a nutrient-dense food that should be a part of any well-balanced diet.

In addition to promoting human health, pistachios' distinct nutritional profile makes them a well-liked snack food with rising demand in both home and foreign markets. While still on the tree, pistachios may naturally develop shell cracks before harvest, increasing the risk of microbial contamination and insect infestation of the inside nut [4-6]. Because of this vulnerability to contamination, food safety requires cautious handling and processing procedures.

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It is customary to collect pistachios by hand in most of countries, dry them using traditional techniques, and then shell them by hand. The high humidity and temperature conditions that are common during storage increase the danger of microbial infection, which ultimately prevents consumers from accessing safe food, even though these procedures may preserve some elements of quality [7, 8]. Furthermore, both growers and processors are financially concerned about the possibility of post-harvest losses brought on by microbial spoiling. Among the most concerning contaminants are *Aspergillus* species, particularly *Aspergllus*. *flavus* and *Aespergillus parasiticus*, which produce aflatoxins-highly toxic compounds that pose serious health risks. These fungi have a strong affinity for oil-rich nuts, including pistachios, and their spores are commonly found in the air, soil, and agricultural 82 environments. They can grow within a temperature range of 10 °C to 45 °C, with optimal growth occurring between 25 °C and 28 °C [1, 2]. Due to the health risks associated with aflatoxin contamination, many countries have established regulatory limits on acceptable levels in food products [3].

Apart from fungal contamination, pistachios can also harbor pathogenic bacteria. Microorganisms such as *Escherichia coli*, *Bacillus cereus*, *Klebsiella*, and *Salmonella* spp. have been identified as potential contaminants, posing health concerns for consumers. While the low water activity of dried pistachios inhibits bacterial growth, it does not necessarily eliminate bacterial survival. Under suitable environmental conditions, bacterial spores can become active, potentially leading to foodborne illnesses. Proper handling, storage, and microbial control measures are essential to minimize contamination and ensure the safety of pistachios for consumers [4-6]. To overcome these obstacles, non-thermal processing techniques have been created that efficiently inactivate microorganisms without sacrificing the pistachios' chemical, physical, and sensory qualities [9]. Because they can improve food safety while preserving product quality, these techniques are especially beneficial and appealing to both producers and consumers. One prominent technique is the use of UV-C radiation, which has become popular recently as a viable substitute for conventional thermal processing methods. UVA, UVB, and UVC light are the three types of UV light; UV-C is very useful for disinfection because of its germicidal qualities. Because it may inactivate a variety of pathogens, such as bacteria, viruses, and fungi, this wavelength range is a desirable choice for improving food safety [10-12]. Moreover, pulsed electric fields (PEF), pulsed light, irradiation, power ultrasound, and cold plasma also carry the potential to process pistachio nuts with microbial inactivation [7, 8] even though special equipment design may require to process pistachio nuts to achieve a significant level of microbial inactivation. Therefore, this study's goal is to find out how well UV-C technology works to lower the while maintaining the pistachios' quality attributes, this study seeks to provide important information about the use of alternative non-thermal processing techniques in the food sector.

2. Materials and methods

2.1 *Pistachio samples*

Adagro Food and Agriculture Machinery Industry and Trade Limited Company (Gaziantep, Turkey) provided the Antep Pistachios (*Pistacia vera* L.). Before being used for the treatments, the samples were vacuum-packed and kept in a refrigerator.

2.2 *Laboratory scale UV-C system*

The laboratory-scale UV-C system, designed as a closed cabinet, consists of UV lamps, a motor, and an electrical panel to control the process. The system is equipped with ten UV-C lamps (90 cm in length, emitting at 254 nm, Philips, China), positioned 30 cm above a vibrating conveyor belt to ensure uniform exposure of pistachio kernels to UV-C radiation. The lamps are spaced 10 cm apart to maximize coverage and minimize shadowing effects.

To achieve consistent UV-C dose distribution, the pistachio kernels were subjected to continuous movement on the vibrating conveyor belt, which induced a tumbling motion, ensuring even surface exposure. Uneven exposure could result in variations in microbial reduction efficiency and sensory properties, such as texture and flavor. Therefore, the system was carefully designed to optimize energy absorption by all kernels. The UV-C dose (J/cm^2) was determined using the equation:

$$F = I \times t \tag{1}$$

where F represents the UV-C dose (J/cm^2), I is the light intensity of the lamp (W/cm^2), and t is the process time (s).

To establish the most effective treatment conditions while maintaining product quality, preliminary trials were conducted to determine the appropriate UV-C doses. The doses applied in this study (39.6, 79.2, and 118.8 J/cm^2) were selected based on microbial inactivation efficacy and their impact on physicochemical and sensory attributes (Table 1). Higher doses were evaluated to ensure an enhanced reduction of pathogens such as *Salmonella* spp., while lower doses were assessed to minimize potential oxidative changes. The uniformity of UV-C exposure was verified by measuring light intensity at multiple points across the conveyor belt using a radiometer, ensuring that pistachio kernels received a consistent dose throughout the process. This experimental setup effectively balances microbial reduction and product integrity, demonstrating the feasibility of integrating UV-C treatment into industrial processing lines for enhancing the safety and quality of pistachios.

Table 1. UV-C treatment parameters applied to pistachios

UV-C lght intensity (W/cm^2)	UV-C time (s)	UV-C dose (J/cm^2)
0.044	900	39.6
0.044	1,800	79.2
0.044	2,700	118.8

2.3 *Titratable acidity (TA)*

A 1 g sample of pistachios was finely crushed using a blender, after the addition of 10 mL of a 1 : 1 diethyl ether-ethyl alcohol mixture. Titration of the solution was performed with 0.1 N NaOH using 1% phenolphthalein as a titration indicator [9]. The titratable acidity value was calculated (Equation (2)) using the formula below.

$$TA\left(\frac{g}{100\,g}\right) = \frac{V \times F \times E \times 100}{M} \tag{2}$$

where V is the volume of 0.1 N NaOH spent (mL), F is the normality of NaOH solution used in titration, M is the actual amount of titrated sample (g) and E is the amount of acid equivalent to 1 mL 0.1 N NaOH (g).

2.4 *Color measurement*

Color L^* value represents lightness (0 = black, 100 = white), the a^* value indicates the red-green axis (negative values toward green, positive values toward red), and the b^* value represents the blue-yellow axis (negative values toward blue, positive values toward yellow), allowing precise color measurement using the Minolta colorimeter in the color science imaging (CSI) system (Konica CM-700d, Nieuwegein, Netherlands). Calculation of chroma, hue, total color difference (TCD), and browning index (BI) values were driven from the measured color values [10].

2.5 *Oil content determination*

Glass flasks were dried to a consistent weight before extraction, chilled in a desiccator, and then weighed. Filter paper-covered cellulose extraction cartridges were filled with around five grams of ground pistachio sample. A 150 mL of hexane was utilized as the extraction solvent and following extraction, the samples were chilled in a desiccator and reweighed after evaporation of hexane around 105 °C [11].

2.6 *Peroxide value*

Approximately 4 grams of pistachio samples after grinding were taken, and 7.0 mL of hexane was introduced to extract the oil. Next, 20 mL of a chloroform-acetic acid mixture (2 : 3 ratio) and 0.4 mL potassium iodide solution were added. The mixture was shaken vigorously, and the conical flask was kept sealed for 5 min in a dark environment. Afterward, 30 mL pure water and 2 mL 1% chlorine solution were added to the mixture. Subsequently, 200 mL of starch solution was introduced to release the iodine. Titration was performed with 0.01 N sodium thiosulfate solution in the presence of 1% starch solution to measure the quantity of iodine (Equation (3)) [9].

$$\text{Peroxide value (meq O}_2\text{ / kg oil)} = \frac{((a-b)\times N\times 1{,}000)}{m} \tag{3}$$

where *a* is the volume of thiosulfate spent for the titration sample in milliliters, *b* is the volume of thiosulfate spent for the blank in the titration in milliliters, *N* is the thiosulfate's normality, and *m* is the sample amount in grams.

2.7 *Total phenolic substance content*

A 100 g pistachio sample was ground using a blender, and 500 mL of 80% acetone was added. After filtration, a 20 µL portion of the filtrate was diluted with 180 µL of distilled water. To this diluted sample, 2,600 µL of distilled water, 400 µL of Folin-Ciocalteu solution, and 2,000 µL of 7.5% Na_2CO_3 solution were added, making a total volume of 5 mL. A blank solution was prepared by combining 2,800 µL of distilled water, 200 µL of Folin-Ciocalteu solution, and 2,000 µL of Na_2CO_3 solution, followed by a 5-minute incubation. Absorbance readings (Nüve HACH LANGE, DR 5,000) were recorded at 760 nm [12]. The pre-prepared standard gallic acid curve was used to calculate the total phenolic substance content (TPSC) of the pistachio samples based on the absorbance values obtained from the spectrophotometer readings.

2.8 *Total chlorophyll content*

After blending five grams of the ground pistachio samples in 25 milliliters of acetone at 80% concentration, the samples were filtrated. The absorbance values of the resultant filtrate were measured at 663 and 645 nm to ascertain the total amount of chlorophyll [13].

2.9 *Total antioxidant activity*

The pistachio samples were first ground using a blender, and then 2 g of the ground sample was mixed with 10 mL of 80% acetone. The mixture was filtered through filter paper and 200 µL of the pistachio extract was removed and diluted with 4,800 µL of distilled water. Finally, 100 µL of the diluted sample was taken and combined with 900 µL of Tris-HCl buffer and 1,000 µL of 2,2-Diphenyl-1-picrylhydrazyl (DPPH) solution. The mixture was homogenized by vortexing. The samples were then incubated in the dark for half an hour, after which the absorbance was measurement at 517 nm [13].

$$\%AA = \left(1 - \frac{Abs_{sample}}{Abs_{blank}}\right)\times 100 \tag{4}$$

2.10 *Analysis of fatty acid composition*

Gas chromatography (GC) with a flame ionization detector (FID) (Shimadzu QP2020, Shimadzu Corp., Kyoto, Japan) was used to examine the fatty acid composition. The system was equipped with a Rtx-2330 capillary column (0.20 µm film thickness, 60 m length, 0.25 mm internal diameter, Restek, Bad Homburg, Germany) to analyze the samples. Extraction and the analysis were conducted at Mardin Artuklu University's Central Research Laboratory in

Mardin, Turkey [11].

2.11 *Microbiological analyses*

25 g of the samples were placed into Falcon tubes and diluted with 225 mL of 0.1% peptone water. Then, dilutions to be plated were selected and plated on xylose lysine dextrose (XLD) agar for total *Salmonellae* count, plate count agar (PCA) (Fluka, Seelze, Germany) for total mesophilic aerobic bacteria (TMAB) count, potato dextrose agar (PDA) for total mold and yeast count, violet red bile agar (VRBA) for total coliform count by spread plating method under aseptic conditions. The XLD petri dishes were incubated for 3-5 days at 34 ± 2 °C for total *Salmonella* spp. count, PCA plates for TMAB and VRBA plates for total coliform counts were incubated for 24-48 hours at 35 ± 2 °C, and PDA plates were incubated for 3 to 5 days at 22 ± 2 °C, respectively [14]. While Fluka (Seelze, Germany) supplied the agars, Sigma Aldrich (Steinheim, Germany) acquired the chemicals.

2.12 *Sensory analysis*

Changes in sensory properties of pistachios were measured by a 9-point hedonic scale descriptive sensory analysis with 36 trained panelists [14]. The panelists evaluated various quality characteristics including appearance, flavor-aroma, taste, texture, color, and aftertaste.

2.13 *Data analyses*

The data analysis was performed by utilization of a one-way analysis of variance (ANOVA) test and Tukey's multiple comparison test (MINITAB 17.0, Minitab, Inc., State College, PA), with a significance level set at $P \leq 0.05$. principal component analysis (PCA) was performed to reduce the dimensionality of the dataset and identify the underlying structure of the variables. The analysis was conducted on multiple variables including UV-C time (s), UV-C dose (J/cm^2), total phenolic substance content (TPSC), titratable acidity (TA), total chlorophyll content (TCC), color parameters, microbial inactivation, sensory characteristics, and fatty acids. The eigenvalues and cumulative variance explained by each principal component (PC) were examined. All experiments were conducted in triplicate.

3. Results and discussion

Fat content is a key quality attribute for pistachios, as it significantly affects their nutritional value, flavor profile, and texture. These fats not only provide essential fatty acids but also play a crucial role in the pistachio's taste and mouthfeel, enhancing the creamy and rich flavor that consumers expect. Additionally, the fat content influences the pistachio's shelf life, as higher fat levels make the product more prone to oxidation, which can lead to rancidity over time [15-18]. TA is a crucial quality parameter for pistachios, as it significantly influences their flavor, shelf life, and overall consumer acceptance. The acidity level helps determine the taste profile of pistachios, with balanced acidity contributing to a pleasant, mild flavor, while elevated levels may lead to sour or off-flavors. Additionally, titratable acidity can serve as an indicator of freshness and potential spoilage, as changes in acidity may signal microbial activity or chemical degradation, particularly the oxidation of fats, which can lead to rancidity. Thus, maintaining appropriate acidity levels helps to preserve the overall quality and marketability of pistachios [19, 20]. The TA of the untreated pistachio nuts measured as 0.69 ± 0.00 g/100 g did not change with increased treatment time ($P > 0.05$) (Table 2). The total fat content of the pistachio samples 42.52 ± 2.36% showed a significantly increased trend from 46.40 ± 3.12% to 49.52 ± 2.70% with increased energy from 39.6 to 118.8 J/cm^2 ($P \leq 0.05$) (Table 2).

Peroxide value is a key indicator of the oxidative rancidity in pistachios, making it an important measure for assessing their quality and shelf life. Monitoring peroxide value is critical for detecting rancidity before it affects the flavor, aroma, and safety of pistachios, as advanced oxidation can lead to off-flavors and potential health risks from consuming oxidized fats. A higher peroxide value is typically associated with inferior quality and sensory attributes, which impacts the production's economic worth [21-23]. The mean initial peroxide value of the pistachios was measured as 4.75 ± 0.60 meq O_2/kg increased to 5.25 ± 0.48 meq O_2/kg with applied UV-C treatment ($P \leq 0.05$) (Table

2). Even though UV-C treatment significantly increased the peroxide value of pistachios, it remained below the rancidity threshold, which typically ranges between 5 and 10 milliequivalents of peroxide per kilogram of fat (meq O_2/kg fat). Keeping peroxide values below this threshold is crucial for ensuring the freshness and marketability of pistachios.

Table 2. Effects of UV-C treatment on titratable acidity and peroxide value of pistachios

UV-C dosage (J/cm^2)	Total fat content (%)	Titratable acidity (g/100 g)	Peroxide value (meq O_2/kg)
0	42.52 ± 2.36^b	0.69 ± 0.20^a	4.75 ± 0.60^b
39.6	46.40 ± 3.12^{ab}	0.69 ± 0.32^a	5.25 ± 0.38^a
79.2	46.65 ± 2.94^{ab}	0.69 ± 0.18^a	5.25 ± 0.44^a
118.8	49.52 ± 2.70^a	0.69 ± 0.28^a	5.25 ± 0.48^a

* Data in the same column with different superscript letters are significantly different ($P \leq 0.05$)
** Data is presented as mean ± standard deviation

Color is a key factor in determining the quality of pistachios since it indicates their ripeness, freshness, and general attractiveness. High-quality pistachios are frequently identified by their vivid green color, although deterioration or uneven coloring may be a sign of poor processing, aging, or storage conditions. In addition to having an effect on consumer perception, color plays a crucial role in quality control procedures, affecting price, marketability, and grading in both home and foreign markets [20]. The *L**, *a**, and *b** color parameters provide standardized, reproducible assessments of pistachio quality, enabling effective quality control across processing and retail sectors [24-26]. The mean initial *L**, *a**, *b** values, chroma, hue TCD, and BI of the untreated pistachio samples of 39.28 ± 0.53, 14.33 ± 0.22, 9.11 ± 0.07, 16.99 ± 0.15, 0.57 ± 0.01, 0.00 ± 0.00, and 40.32 ± 0.33 were significantly changed by applied treatments. While *L**, *b**, hue, and TCD values significantly increased to 46.04 ± 1.04, 10.35 ± 0.27, 0.98 ± 0.01, and 10.07 ± 0.62, *a** and BI values significantly decreased to 7.01 ± 0.04, and -44.67 ± 0.62 ($P \leq 0.05$), respectively (Table 3).

Table 3. Effects of UV-C treatment on color properties of pistachios

UV-C dosage (J/cm^2)	*L**	*a**	*b**	Chroma	Hue	Total color difference	Browning index
0	39.28 ± 0.53^c	14.33 ± 0.22^a	9.11 ± 0.07^b	16.99 ± 0.15^a	0.57 ± 0.01^c	0.00 ± 0.00^d	40.32 ± 0.33^a
39.6	42.26 ± 0.42^b	8.55 ± 0.10^b	10.31 ± 0.31^a	13.40 ± 0.30^b	0.88 ± 0.02^b	6.66 ± 0.30^c	-5.83 ± 0.26^b
79.2	42.49 ± 0.70^b	7.24 ± 0.20^c	10.26 ± 0.16^a	12.56 ± 0.22^c	0.96 ± 0.01^a	7.88 ± 0.41^b	-30.10 ± 0.69^c
118.8	46.04 ± 1.04^a	7.01 ± 0.04^c	10.35 ± 0.27^a	12.50 ± 0.25^c	0.98 ± 0.01^a	10.07 ± 0.62^a	-44.67 ± 0.62^d

* Data in the same column with different superscript letters are significantly different ($P \leq 0.05$)
** Data is presented as mean ± standard deviation

TCC is an important indicator of pistachio quality, especially in terms of its maturity, freshness, and market appeal. Monitoring total chlorophyll content allows producers to determine optimal harvest times, ensuring that pistachios are collected at their peak for superior taste, quality, and longer shelf life [25-27]. The mean initial TCC of the pistachio samples 11.08 ± 0.02 mg/100 g was significantly reduced from 7.64 ± 0.30 mg/100 g at 39.6 J/cm^2 to 6.35 ± 0.32 mg gallic acid equivalent (GAE)/100 g at 118.8 J/cm^2 ($P \leq 0.05$) (Table 4).

The nutritional value, taste, and shelf life of pistachios are all significantly influenced by their total antioxidant activity (TAA). Antioxidant qualities also add to its allure as a functional food, providing dietary advantages as well as natural protection against cellular damage [28-30]. The mean initial TAA of pistachio samples of 30.31 ± 6.46%

significantly increased by treatment time, and it changed from 39.49 ± 0.92% to 51.61 ± 1.46% from 39.6 J/cm^2 to 118.8 J/cm^2 revealing 30.70% increase ($P \leq 0.05$) (Table 4).

Because it plays a major role in the nut's health-promoting qualities, the total phenolic substance content (TPSC) of pistachios is essential. Phenolic compounds help give pistachios their unique flavor and scent, two sensory attributes that are crucial for customer preference and marketability [16, 30, 31]. Therefore, preserving TPSC in pistachios is of great importance. The TPSC of untreated pistachio samples was 290.99 ± 0.29 mg GAE/100 g. Upon application of UV-C energy, the TPSC significantly increased from 291.10 ± 1.40 mg GAE/100 g at 39.6 J/cm^2 to 298.00 ± 0.20 mg GAE/100 g at 118.8 J/cm^2 ($P \leq 0.05$) (Table 4).

Table 4. Effects of UV-C treatment on bioactive properties of pistachios

UV-C dosage (J/cm^2)	Total chlorophyll content (mg/100 g)	Total antioxidant activity (%)	Total phenolic substance content (mg GAE/100 g)
0	11.08 ± 0.92^a	30.31 ± 4.46^c	290.99 ± 0.29^b
39.6	7.64 ± 0.30^c	39.49 ± 0.92^b	291.10 ± 1.40^b
79.2	8.51 ± 0.44^b	39.26 ± 0.74^b	295.50 ± 1.19^b
118.8	6.35 ± 0.32^d	51.61 ± 1.46^a	298.00 ± 0.20^a

* Data in the same column with different superscript letters are significantly different ($P \leq 0.05$)
** Data is presented as mean ± standard deviation

The nutritional value, shelf life, and general quality of pistachios are all significantly influenced by their fatty acid makeup. The oxidative stability of pistachios is strongly impacted by the ratio of unsaturated to saturated fats and the balance of other fatty acid types. It is well-recognized that monounsaturated fatty acids, such as oleic acid, have positive effects on oxidative stability. By slowing down the pace at which lipids oxidize, oleic acid, a predominant monounsaturated fat, increases resistance to rancidity. This leads to a longer shelf life, which helps maintain the flavor and freshness of the pistachio over time. Pistachios' nutritional composition is influenced by polyunsaturated fatty acids, such as linoleic acid (an omega-6 fatty acid), in addition to oleic acid. Compared to monounsaturated fats, polyunsaturated fats are more susceptible to oxidation, even though they offer vital fatty acids for human health. Therefore, preserving the nuts' sensory appeal and health advantages depends on striking the correct balance between these fats. Although they are found in smaller amounts in pistachios, saturated fats do not provide the same oxidation-preventive benefits as unsaturated fats. A less desirable fatty acid profile in terms of nutrition and shelf life may result from the presence of large quantities of saturated fats.

Furthermore, the health benefits of pistachios are associated with their fatty acid content. Higher quantities of monounsaturated fats, such as oleic acid, which is frequently present in olive oil, have been linked to better cardiovascular health by lowering bad cholesterol and enhancing heart health in general. Because of this, pistachios are a healthy snack to include in a balanced diet. Pistachios' fatty acid concentration affects their oxidative stability, which is also affected by outside variables like temperature, light exposure, and storage conditions. By delaying the oxidation process, proper packing and storage techniques, such as vacuum-sealing and refrigeration, help preserve the nuts' quality. Pistachios' fatty acid concentration affects their oxidative stability, which is also affected by outside variables like temperature, light exposure, and storage conditions. By delaying the oxidation process, proper packing and storage techniques, such as vacuum-sealing and refrigeration, help preserve the nuts' quality [31-33].

The fatty acid composition of untreated pistachio samples revealed that 25 different fatty acids were detected in pistachios. Even though the majority of the fatty acids were present in modest concentrations, oleic acid had the highest concentration at 57.30 ± 2.55%, followed by butyric acid at 20.24 ± 1.05%, linolenic acid at 11.96 ± 0.21%, palmitic acid at 6.74 ± 0.31%, and stearic acid at 1.90 ± 0.02%. After exposure to 39.6 J/cm^2, these concentrations changed to 50.87 ± 2.07%, 29.81 ± 0.97%, 11.84 ± 0.53%, 5.92 ± 0.10%, and 1.60 ± 0.02%, respectively. For 79.2 J/cm^2, the values were 49.82 ± 1.87%, 31.99 ± 2.03%, 10.90 ± 0.33%, 5.70 ± 0.32%, and 1.60 ± 0.11%, respectively. At 118.8 J/cm^2, the concentrations were 53.09 ± 1.66%, 27.17 ± 1.13%, 11.26 ± 0.54%, 6.79 ± 0.15%, and 1.76 ± 0.03%, consequently (Table 5).

Table 5. Effect of UV-C treatment on fatty acid composition (%) of pistachios

	Energies (J/cm^2)			
Fatty acids	0	39.6	79.2	118.8
Butyric acid	20.24 ± 1.05^b	29.81 ± 0.97^a	31.99 ± 2.03^a	27.17 ± 1.13^a
Myristic acid	0.08 ± 0.02^a	0.07 ± 0.00^a	0.07 ± 0.00^a	0.07 ± 0.00^a
Myristoleic acid	0.15 ± 0.00^a	0.01 ± 0.00^b	NI	NI
Pentadecanoic acid	NI	0.01 ± 0.00^a	0.01 ± 0.00^a	0.01 ± 0.00^a
Palmitic acid	6.74 ± 0.31^a	5.92 ± 0.10^b	5.70 ± 0.32^b	6.79 ± 0.15^a
Palmiteloic acid	0.41 ± 0.02^a	0.39 ± 0.00^a	0.38 ± 0.00^a	0.39 ± 0.00^a
Heptadecanoic acid	0.04 ± 0.00^a	0.03 ± 0.00^b	0.03 ± 0.00^b	0.03 ± 0.00^b
Cis-10-heptadecanoic acid	0.04 ± 0.00^a	0.04 ± 0.00^a	0.04 ± 0.00^a	0.04 ± 0.00^a
Stearic acid	1.90 ± 0.02^a	1.60 ± 0.02^b	1.60 ± 0.11^b	1.76 ± 0.03^{ab}
Elaidic acid	0.02 ± 0.00^b	0.08 ± 0.00^a	0.02 ± 0.00^b	0.10 ± 0.00^c
Oleic acid	57.30 ± 2.55^a	50.87 ± 2.07^{bc}	49.82 ± 1.87^c	53.09 ± 1.66^b
Linolelaidic acid	0.01 ± 0.00^a	NI	NI	0.01 ± 0.00^a
Linolenic acid	11.96 ± 0.21^a	11.84 ± 0.53^a	10.90 ± 0.33^b	11.26 ± 0.54^a
Arachidic acid	0.17 ± 0.08^a	0.15 ± 0.06^a	0.14 ± 0.06^a	0.16 ± 0.06^a
Alpha-Linolenic acid	0.39 ± 0.00^a	NI	NI	NI
Behenic acid	0.08 ± 0.00^a	0.09 ± 0.00^a	0.08 ± 0.00^a	NI
Cis-11,14,17-eicosatrienoic acid	0.02 ± 0.00^c	0.02 ± 0.00^c	0.34 ± 0.00^a	0.09 ± 0.00^b
Erucic acid	NI	0.01 ± 0.00^a	0.01 ± 0.00^a	NI
Heneicosanoic acid	NI	0.01 ± 0.00^a	NI	0.01 ± 0.00^a
Eicosadienoic acid	NI	0.01 ± 0.00^a	0.01 ± 0.00^a	NI
Behenic acid	NI	0.09 ± 0.00^a	0.08 ± 0.01^a	0.09 ± 0.00^a
Tricosanoic acid	0.60 ± 0.00^a	0.02 ± 0.00^b	0.01 ± 0.00^c	0.01 ± 0.00^c
Lignoceric acid	0.02 ± 0.00^b	0.04 ± 0.00^a	0.04 ± 0.00^a	0.04 ± 0.00^a
Nervonic acid	NI	0.02 ± 0.00^a	0.02 ± 0.00^a	0.02 ± 0.00^a
Cis-4,7,10,13,16,19-docosahexanoic acid	0.07 ± 0.01^a	0.06 ± 0.01^a	0.06 ± 0.01^a	0.07 ± 0.01^a

* Data in the same row with different superscript letters are significantly different ($P \leq 0.05$)
** Data is presented as mean ± standard deviation
*** NI = Non identified

Because high microbial loads can negatively impact pistachios' flavor, texture, and overall quality during processing and storage due to spoiling, as well as the presence of pathogenic bacteria, molds, and yeast, reducing the endogenous microflora in pistachios is crucial for maintaining food safety and extending shelf life. The mean initial counts for TMAB, TMY, total *Salmonellae* spp., and total coliforms were recorded as 4.46 ± 0.15, 5.30 ± 0.34, 4.88 ± 0.23, and 4.43 ± 0.31 log cfu/g, respectively. An increase in energy input led to a significant reduction in microbial counts, revealing 1.36 ± 0.28, 1.92 ± 0.34, 1.68 ± 0.40, and 1.46 ± 0.44 log cfu/g survival levels for TMAB, TMY, total *Salmonellae* spp., and total coliforms, respectively ($P \leq 0.05$) (Table 6).

Table 6. Effects of UV-C treatment on inactivation of endogenous microflora

UV-C dosage (J/cm^2)	TMAB (log cfu/g)	TMY (log cfu/g)	Total *Salmonellae* (log cfu/g)	Total coliform (log cfu/g)
0	4.46 ± 0.15^a	5.30 ± 0.34^a	4.88 ± 0.23^a	4.43 ± 0.31^a
39.6	3.96 ± 0.39^{ab}	4.04 ± 0.91^{ab}	4.33 ± 0.27^a	3.23 ± 0.89^a
79.2	3.33 ± 0.31^b	2.58 ± 0.62^b	2.95 ± 0.46^b	3.06 ± 0.82^a
118.8	1.36 ± 0.28^c	1.92 ± 0.34^c	1.68 ± 0.40^c	1.46 ± 0.44^c

* Data in the same column with different superscript letters are significantly different ($P \leq 0.05$)
** Data is presented as mean ± standard deviation

Texture, taste, flavor-aroma, and appearance are some of the pistachios' sensory attributes that have a significant impact on marketability and customer satisfaction. Together, these characteristics shape consumer preferences and quality perceptions, defining the dining experience. For example, pistachios' distinctive crunchiness and nutty flavor are major factors in their attraction, and any deviation-like rancidity or off flavors-can seriously affect customer confidence. Visual features like uniform color and size add to their aesthetic appeal and perceived quality, while aroma-often connected to freshness and roasting-further enriches the sensory experience. Furthermore, pistachios' viability for a range of culinary applications-from snacks to desserts-is largely determined by their sensory qualities, underscoring their significance for product innovation and diversification as well as customer acceptability.

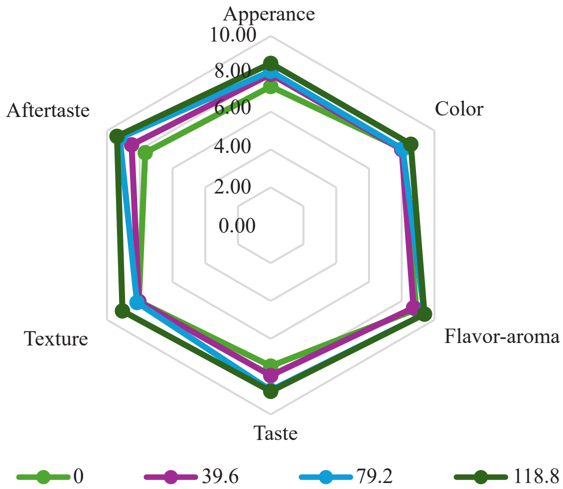

Figure 1. Changes in the sensory properties of pistachios by UV-C treatment

The sensory characteristics of untreated pistachio samples were measured as 7.33 ± 0.48, 8.06 ± 0.42, 8.89 ± 0.19, 8.06 ± 0.92, and 7.67 ± 0.58 for appearance, color, flavor-aroma, taste, texture, and aftertaste, respectively. Measured sensory qualities increased when UV-C energy exposure was increased from 39.6 to 118.8 J/m^2. Indeed, these values rose to 8.55 ± 0.07, 856 ± 0.51, 9.39 ± 0.35, 8.78 ± 0.48, 9.06 ± 0.42, and 9.39 ± 0.35, respectively, with the greatest UV-C energy application of 118.8 J/m^2 ($P < 0.05$) (Figure 1).

Following UV-C treatment, the panelists specifically observed several beneficial changes in the pistachios. The kernels' overall appeal was increased as their green hue grew more vivid and eye-catching. The assessors also expressed great appreciation for the treatment's notable improvement in the pistachios' texture, which made the kernels exceptionally crisp. The simplicity with which the kernels' silver skin could be removed following treatment was another significant finding; this feature enhances the product's utility and convenience. These combined results imply that UV-C treatment may enhance pistachios' visual and sensory appeal while also providing useful benefits for both food processors and consumers.

Because they have a direct impact on marketability and customer acceptance, pistachios' sensory qualities are essential. Pistachios' flavor, texture, and appearance all affect how desirable they are and how they taste when eaten. It is important to combine the natural sweetness and nutty flavor of pistachios with their texture, which should be crunchy but not overly firm. Additionally important in drawing in customers is the aesthetic appeal, which includes the vivid green hue and the well-formed, crisp shell. Pistachio manufacturers and marketers must prioritize high-quality sensory qualities to preserve product consistency and quality since they are critical for guaranteeing consumer happiness, brand loyalty, and repeat business.

The PCA was conducted on the correlation matrix with row-wise variance estimation and resulted in 11 principal components that together explain 100% of the dataset's variability. The first component has an eigenvalue of 12.32 and explains 56.0% of the variance, while the second and third components account for 22.8% and 9.0%, respectively; the remaining components contribute progressively lower proportions. The eigenvectors reveal that UV-C time and UV-C dose have similar and strong loadings on the first component, whereas other variables such as TPSC, total antioxidant activity (TAA), and TCC show distinct loading patterns on the subsequent components, highlighting diverse underlying dimensions related to microbial counts, color metrics, and chemical properties. In addition, a variable clustering analysis grouped the features into four clusters: Cluster 1, represented by TCC and comprising 11 variables, explains 42.5% of the variation; cluster 2, represented by titratable acidity with 5 variables, explains 19.2%; cluster 4, centered on Hue with 3 variables, explains 11.5%; and cluster 3, with TPSC as the representative variable and 3 members, accounts for 9.2% of the variation. Overall, the clusters explain 82.4% of the variation, which reinforces the multidimensional structure identified by the PCA.

The projection of samples onto the plane revealed a discernible distribution pattern, suggesting inherent heterogeneity within the sample set based on the measured variables (Figure 2). Variables with longer vectors exhibited a greater influence on the principal components, while the direction of the vectors indicated the nature of their correlation. For example, the clustering of Hue, *b**, and *L** vectors in the positive quadrant of PC2 suggests a positive correlation among these colorimetric parameters and their association with samples exhibiting higher scores along this component. Conversely, the opposing direction of vectors such as total *Salmonellae* and total coliform relative to firmness/hardness and tenderness/softness indicates a potential negative correlation between these sets of attributes across the sample population. These results provide a quantitative framework for understanding the complex interplay of quality parameters and their contribution to the observed variability among the samples.

The PCA analysis derived three principal components that collectively explain 100% of the variance, with Component 1 accounting for 71.47%, Component 2 for 19.48%, and Component 3 for 9.05%. The eigenvectors reveal how each variable-including various fatty acids and UV dose-contributes to these components, with the direction and magnitude of loadings indicating the strength and nature of these associations. Furthermore, a variable clustering approach grouped the variables into three clusters: Cluster 1, represented by tricosanoic acid, explains about 50.3% of the total variation; cluster 2, led by Cis-4,7,10,13,16,19-docosahexan, accounts for 19.1%; and cluster 3, dominated by behenic acid, contributes approximately 21.3%. Overall, the clusters explain 90.8% of the variation, and the standardized component coefficients demonstrate that most variables strongly associate with one cluster while showing negligible contributions to the others, thereby emphasizing the distinct underlying data structure.

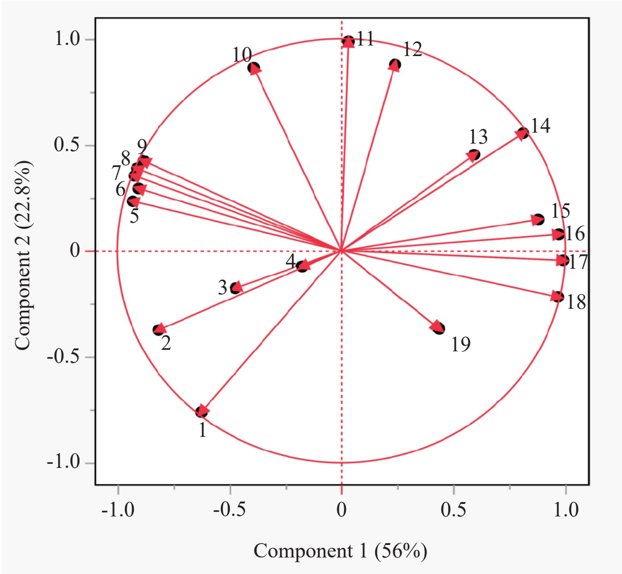

Figure 2. A loading/biplot for physicochemical and sensory properties and microbial inactivation (1: *a**, 2: TAA, 3: TPSC, 4: flavor-aroma, 5: Chroma, 6: Total coliform count, 7: total mold and yeast count (TMY), 8: Total *Salmonellae*, 9: total mesophilic aerobic bacteria count (TABC), 10: *b**, 11: Hue, 12: *L**, 13: Titratable acidity, 14: Proxide value, 15: Aftertaste, 16: Total fat content, 17: Taste, 18: TCC, 19: Texture)

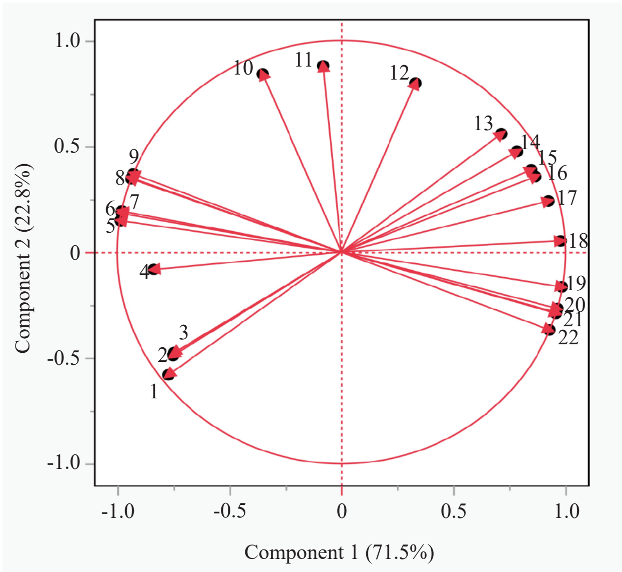

Figure 3. A loading/biplot for fatty acids (1: Pentadecanoic acid, 2: Linolenic acid, 3: Behenic acid, 4: UV dose, 5: Nervonic acid, 6: Butyric acid, 7: Lignoceric acid, 7: Cis-11-eicosenoic acid, 8: Palimitic acid, 9: Stearic acid, 10: Elaidic acid, 11: Olec acid, 12: Cis-10-heptadecanoic acid, 13: Behenic acid, 14: Cis-4,7,10,13,16,19-Docosahexanoic acid, 15: Arachidic acid, 16: Linolelaidic acid, 17: Palmiteloic acid, 18: Cis-11,14,17-eicosatrienoic acid, 19: Tricosanoic acid, 20: Myristoleic acid, 21: Heptadecaonic acid, 22: Alpha-linolenic acid)

The sample plot (Figure 3) visualized the distribution of samples in the reduced two-dimensional space defined by PC1 and PC2, revealing some degree of sample separation primarily along the first principal component. Several saturated fatty acids exhibited positive correlations and loaded strongly onto the positive side of both PC1 and PC2. Notably, the UV dose variable appeared to be associated with samples exhibiting lower scores on PC1, suggesting a potential inverse relationship with the aforementioned saturated fatty acids. These findings highlight the key variables driving the variance in the dataset and provide insights into the potential influence of UV dose on the fatty acid profiles of the samples.

The chemical and sensory characteristics of pistachios are affected by outside variables and processing parameters including temperature, humidity, and storage conditions as they are extremely sensitive products. These factors affect its flavor, texture, and nutritional value, but they also increase the risk of quality deterioration over time. Additionally, pistachios are susceptible to microbial contamination and fungal development, particularly from *Aspergillus* species that produce harmful mycotoxins like aflatoxins, which can be very harmful to human health. Therefore, pistachio treatment research often focuses on microbial inactivation and mycotoxin reduction employing advanced technologies like thermal processing, irradiation, chemical treatments, and biocontrol approaches. These techniques aim to ensure the safety and quality of pistachios while maintaining their delicious sensory appeal to meet both legal standards and customer expectations.

UV treatment has gained popularity for pathogen control due to its affordability and ease of use. However, its efficacy depends on several factors, including the product's characteristics (e.g., color, transparency) [34], exposure duration, the type of microorganisms involved, and the UV wavelength used [35]. In general, longer exposure times and higher UV light intensity lead to more significant mycotoxin reductions.

When compared to the untreated control group, weight loss was significantly decreased by applying UV-C therapy to fresh pistachios at dosages of 2.1 and 4.5 kJ/m^2 utilizing a rotating cylinder system with seven germicidal UV-C lamps. Pistachios treated with UV-C and packaged in non-perforated polyethylene terephthalate (PET) film demonstrated significantly higher enzyme activities, particularly catalase and peroxidase, than the untreated samples. In terms of color attributes, pistachios treated with a 2.1 kJ/m^2 dose and those in the control group, both stored in non-perforated PET film, exhibited higher *L**, *a**, and reduced *b** compared to pistachios treated with 4.5 kJ/m^2. However, the sensory quality of pistachios treated with 4.5 kJ/m^2 treatment was significantly lower than that of both the 2.1 kJ/m^2 treatment and the untreated group [36].

A comparative study evaluating UV-C radiation, gaseous ozone (O_3), and citric acid (CA) treatments of pistachios contaminated with aflatoxin reported that the most effective approach involved immersion in 3 N CA, 30 min of O_3 exposure, and 36 hours of UV-C radiation. The combination of applications degraded more than more than 99% of aflatoxin G1 and G2 and more than 90% of initial aflatoxin B1 and B2. These treatments did not cause significant changes in pistachio fat or protein content, acid and peroxide values, total phenolics, or soluble and insoluble carbohydrates. Sensory attributes such as acidity, sweetness, color, flavor, and overall quality remained similar between treated and untreated samples. The combined treatment was more effective than any single treatment alone [37]. Additionally, studies exploring the effects of UV-A and UV-B radiation on fungal growth in pistachios showed that reducing daily exposure from 16 hours to 6 hours, combined with either dark incubation or alternating dark and light periods over 7 to 21 days, effectively reduced *Aspergillus carbonarius* fungal load [38].

UV-C was also applied to peanuts and almonds after inoculating them with *Salmonella typhimurium*. It was observed that there were no significant changes in the *L**, *a**, and *b** values of the samples following UV-C treatment with a wavelength of 254 nm, applied at a distance of 10 cm for durations ranging from 0 to 30 min. UV-C treatment impacted the physical, chemical, microbiological, and sensory characteristics of almonds and peanuts inoculated with *S. typhimurium*, but did not significantly alter the peroxide values of either peanuts or almonds [39].

The positive effects of UV-C treatment on other fruits have also been studied. For instance, strawberries treated with UV-C radiation for 15 days at 10 °C showed an increase in antioxidant capacity from 21.11% at the start to 32.2% by the end of the storage period [40]. UV light (254 nm) applied to jalapeño peppers at 0.5 J/cm^2, 1 J/cm^2, 2 J/cm^2, and 4 J/cm^2 intensities was effective in reducing *Salmonella* spp. by 3.02 ± 0.06 log cfu/g [41]. Moreover, UV-C treatment applied for 15, 30, and 60 min provided a 1.07 log units reduction in the TMY count in mangoes and 1.3 log units in pineapples. Additionally, when the temperature during treatment was increased to 70 °C, the decrease in TMY counts further increased, showing a reduction of 1.13 log units in mangoes and 1.4 log units in pineapples [42].

Numerous studies have explored the effectiveness of various nonthermal and chemical treatments for reducing microbial contamination in low-moisture foods (LMFs) like pistachios. Plasma treatments using pure oxygen and argon for just one minute were shown to reduce *E. coli* counts on pistachios by 4 logs [43]. Similarly, cold plasma has demonstrated efficacy in reducing bacteria [44] fungal contamination [45] and inhibiting aflatoxin production in hazelnuts [45]. Gamma irradiation, which utilizes gamma rays from a radioactive source, is another effective pasteurization technique. Gamma irradiation has a deeper penetration depth than traditional heating and can efficiently eliminate pathogens in low-moisture foods; its effectiveness is dependent on several variables, including dose, food moisture content, temperature, and meteorological conditions [46]. A 5 kGy gamma irradiation dose effectively reduced populations of *E. coli* O157 : H7, *S. typhimurium*, and *L. monocytogenes* on pistachios to < 1 log cfu/g without altering the color of the nuts [47]. Microwave irradiation as another promising nonthermal technique for microbial inactivation applied at doses of 3,000 and 4,000 W significantly reduced mold counts on the surfaces of pistachios, in-shell almonds, and peanuts [48]. The continuous PEF system, applying 71.23 J/kg of energy and an electric field strength of 28.8 kV/cm, was used to treat pistachios, resulting in reductions of 4.73, 5.21, 5.56, and 4.87 log cfu/g for *Salmonella* spp., TMAB, TMY, and total coliform bacteria, respectively. While the applied energy led to significant increases in peroxide value, total fat content, total antioxidant capacity, total phenolic substance content, and total chlorophyll content, no significant changes were observed in color, total acidity, or sensory attributes [8]. Chemical sanitizers have also been tested for decontaminating pistachios. A combination of peracetic acid and ethanol showed minimal effectiveness, reducing *Salmonella* populations by less than 1 log cfu/g, likely due to the high resistance of the pathogen in low-moisture conditions [49]. More effective treatments included 2% lactic acid or 2% levulinic acid combined with sodium dodecyl sulfate, which achieved reductions of 3.7 and 3.4 log cfu/g, respectively, while a mixed peroxy acid sanitizer at 200 μg/mL reduced *Salmonella* populations by 2.4 log cfu/g [50]. Ozone has also shown potential as a decontamination method; treatment with 160 g ozone/m^3 for 30 minutes reduced *S. enteritidis* population by 0.8 and 2.9 log cfu/g on pistachios and almonds, respectively. Similarly, ozone at 8.88 mg/L for 240 minutes provided more than a 3.10 log reduction in *A. flavus* populations on Brazil nuts [51].

4. Conclusions

Pistachios are a valuable agricultural commodity with significant economic, nutritional, and cultural importance. However, microbial contamination remains a critical food safety challenge, as pistachios are often consumed with minimal processing. This study demonstrates that UV-C light treatment is an effective method for reducing microbial contamination while preserving the sensory, chemical, and physical qualities of pistachios. The treatment achieved significant microbial reductions, including key pathogens such as *Salmonella* spp., with no adverse effects on texture or flavor. Additionally, UV-C exposure enhanced total phenolic content and antioxidant activity, offering potential nutritional benefits.

UV-C treatment presents a practical, non-thermal, and environmentally friendly alternative to traditional microbial control methods. Its ability to inactivate pathogens without the use of chemicals or water makes it a cost-effective and sustainable solution for the pistachio industry. Given its compatibility with existing processing lines, UV-C technology can be seamlessly integrated into post-harvest handling to enhance food safety and meet regulatory standards. Future research should focus on optimizing treatment parameters and assessing long-term storage effects to further support industrial adoption.

Authors' contribution

Project management, methodology, data curation, visualization, ideation, and writing (original draft, review, and editing) are performed by Gulsun Akdemir Evrendilek; whereas data curation and formal analysis and supervision were conducted by Şerife Mustuloğlu and Semra Turan.

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Conflict of interest

The authors declare that they have no conflicts of interest.

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