UV-C radiation and gaseous ozone improve the physicochemical characteristics of refrigerated strawberries

La radiación UV-C y el ozono gaseoso mejoran las características fisicoquímicas de fresas refrigeradas

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ABSTRACT

The use of new preservation techniques, such as the application of gaseous ozone (OZ) and ultraviolet (UV-C) radiation, enables agricultural products to be maintained in optimal conditions for consumers. Additionally, these methods reduce risks to human health by decreasing the presence of pathogens in treated foods. The aim of this study was to evaluate the effect of gaseous ozone and UV-C radiation exposure on the physicochemical characteristics of strawberries. Strawberries were exposed to radiation doses of 0 kJ m^{-2} (control), 2.02 kJ m^{-2}, 3.04 kJ m^{-2}, and 4.05 kJ m^{-2} and to gaseous ozone concentrations of 0.267 and 0.586 mg L^{-1} for 35 and 70 s at each concentration. The experimental units were then packaged in PET packaging and stored at 5±1°C and 85±5% relative humidity (RH) for 5 d. Physicochemical tests included weight loss, color, pH, titratable acidity, total soluble solids, and respiration rate. The UV-C and ozone treatments demonstrated better performance compared to the control maintained at 5±1°C. Notably, the treatments that showed the most favorable outcomes for the physicochemical properties of strawberries were OZ3 (exposure to 0.586 mg L^{-1} of O_3 for 35 s) and UVC3 (exposure to radiation dose of 4.05 kJ m^{-2}), indicating these methods are suitable for the preservation of strawberries.

Key words: ozonation, postharvest quality, ultraviolet radiation, ripening, *Fragaria x ananassa*.

RESUMEN

El uso de nuevas técnicas de conservación, como la aplicación de ozono (OZ) gaseoso y radiación ultravioleta (UV-C), permite mantener los productos agrícolas en condiciones óptimas para los consumidores. Además, estos métodos reducen los riesgos para la salud humana al disminuir la presencia de patógenos en los alimentos tratados. El objetivo de este estudio fue evaluar el efecto de la exposición al ozono gaseoso y a la radiación UV-C sobre las características fisicoquímicas de las fresas. Las fresas fueron expuestas a dosis de radiación de 0 kJ m^{-2} (control), 2,02 kJ m^{-2}, 3,04 kJ m^{-2} y 4,05 kJ m^{-2}, y a concentraciones de ozono gaseoso de 0,267 y 0,586 mg L^{-1} durante 35 y 70 s para cada concentración. Las unidades experimentales se envasaron en empaques de PET y se almacenaron a 5±1°C y 85±5% HR durante 5 d. Las pruebas fisicoquímicas realizadas incluyeron pérdida de peso, color, pH, acidez titulable, sólidos solubles totales y tasa de respiración. Los tratamientos con UV-C y ozono demostraron un mejor rendimiento en comparación con el control mantenido a 5±1°C. Notablemente, los tratamientos que mostraron los resultados más favorables para las propiedades fisicoquímicas de las fresas fueron OZ3 (tratamiento con exposición a 0,586 mg L^{-1} de O_3 durante 35 s) y UVC3 (tratamiento con exposición a dosis de radiación de 4,05 kJ m^{-2}), indicando que estos métodos son adecuados para la conservación de las fresas.

Palabras clave: ozonización, calidad poscosecha, radiación ultravioleta, maduración, *Fragaria x ananassa*.

Introduction

Preserving the quality of fruits and vegetables after harvest is an important matter involving several attributes such as visual appearance, texture, flavor, aroma, nutritional value, and food safety (Bajaj *et al*., 2023). From the perspective of microbiological quality and food safety, it is necessary to guarantee their safety and nutritional value to promote consumer health (Fung *et al*., 2018). In recent years, an aspect that has gained importance is the preservation of agricultural products under optimal conditions to prolong shelf life and reduce microbial load (Gil *et al*., 2015; Snyder & Worobo, 2018). Preservation techniques include irradiation with short-wave ultraviolet light (UV-C), ozone exposure, hydrogen peroxide, and peracetic acid, among others (Shehata *et al*., 2021; Templalexis *et al*., 2023).

Ozone exposure is an ecological and economical alternative for preserving quality in fruits and vegetables, as ozone does not leave any residue in the food. It is also a

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germicidal agent that reduces the microbial load of foods (Sarron *et al*., 2021). Ozone is an oxidizing agent that can be applied in gaseous form or dissolved in water (Sarron *et al*., 2021; Vettraino *et al*., 2020). Its action is based on its high oxidizing power, which provides strong disinfection and sterilization capacity, allowing the sanitizing action to occur with a lower concentration and shorter contact time (Pandiselvam *et al*., 2019). However, it is necessary to use the appropriate concentration, as high concentrations of compounds can affect the nutritional and sensory value of vegetables, altering their color and flavor (Coelho *et al*., 2015).

The use of ultraviolet irradiation to preserve fruits and vegetables has notable effects, such as delaying the ripening of some climacteric fruits, such as tomato (Lu *et al*., 2016), and delaying physiological changes in non-climacteric fruits, such as pepper fruits (Ma *et al*., 2021). In addition, ultraviolet radiation does not produce toxic organic compounds compared to chlorine-based disinfectants (Souza, 2014). Ultraviolet radiation is classified as non-ionizing radiation with a wavelength between 100 and 400 nm and is used in post-harvest preservation of fruits and vegetables due to its ability to reduce microbial load and maintain firmness of the fruits (Peng *et al*., 2022; Singh *et al*., 2021). The maximum inactivation peak is at 254 nm, and it has been shown to be most effective at this wavelength (Bhullar *et al*., 2018).

Ozone exposure doses or UV-C irradiation energies vary depending on the type of agricultural product (Delorme *et al*., 2020). Exposure of tissues to low doses of UV radiation can produce fungicidal compounds such as phytoalexins and delay ripening and senescence processes (Darré *et al*., 2022; Sethi *et al*., 2018). One of the benefits of this treatment is the reduction of postharvest losses caused by physiological disorders such as chilling injury, susceptibility to phytopathogen attack, mechanical damage, and loss of firmness, among others (Lemessa *et al*., 2022). For instance, one of the benefits of UV-C irradiation of strawberries (*Fragaria x ananassa*) is the reduction of firmness loss, a critical factor in postharvest life (Xu *et al*., 2017).

The application of UV-C radiation and ozone treatments to strawberries has been shown to significantly influence their physicochemical properties. Several studies have demonstrated that controlled exposure to UV-C can reduce pathogen incidence, slow respiration rates, and extend the postharvest shelf life of strawberries while preserving key quality attributes (Cote Daza, 2011). Similarly, ozone treatment at optimal concentrations has been reported to effectively reduce microbial load and maintain the sensory quality of strawberries, enhancing their postharvest preservation (Macías-Gallardo *et al*., 2023). These findings support the adoption of UV-C and ozone treatments as viable technologies for maintaining fruit quality and prolonging the postharvest longevity of strawberries (Contigiani, 2019).

Strawberries are among the most accepted and commercialized fruits in the import and export of fresh products, in the frozen food industry, as a flavoring in the preparation of medicines, and others (Gonçalves *et al*., 2018). Although the strawberry is a non-climacteric fruit, it is highly perishable and susceptible to mechanical damage, water loss, and physiological and microbiological deterioration (Gol *et al*., 2013; Qureshi Quarshi *et al*., 2023). The quality characteristics and chemical composition of strawberries are influenced by a combination of several genetic (cultivar) and geographical (climate, soil, among others) factors (Ornelas-Paz *et al*., 2013; Pinheiro *et al*., 2021). The aim of this study is to evaluate the effect of exposure to gaseous ozone (OZ) and UV-C radiation, as product preservation techniques, on the physicochemical characteristics of strawberries.

Materials and methods

Strawberries of the Campinas variety (IAC-2712) were purchased at an intermediate stage of ripening (3/4 red on the surface) at the Brazilian State Supply Centre (CEASA) in Campinas, Brazil, and then taken to the postharvest laboratory at the Faculty of Agricultural Engineering (FEAGRI) of the University of Campinas (UNICAMP). The strawberries had an average length and diameter of 32.4 mm and 25.5 mm, respectively. They were stored at 5±1°C until they were exposed to ozone gas and UV-C radiation.

The effect of two non-thermal preservation techniques, ozone gas exposure and UV-C radiation, on the maintenance of the physicochemical characteristics of strawberries was evaluated. For this purpose, strawberries were exposed to different concentrations of ozone gas at different exposure times and doses of short-wave ultraviolet radiation (UV-C), together with control strawberries packaged in PET packaging and stored at a temperature of 5±1°C. A summary of the treatments is given in Table 1.

TABLE 1. Summary of the treatments applied to the strawberry fruits.

Ozone			UV-C	
Treatment	Concentration (mg L^{-1})	Exposure time (s)	Treatment	Energy (kJ m^{-2})
OZ1	0.586	70	UVC1	2.02
OZ2	0.267	35	UVC2	3.04
OZ3	0.586	35	UVC3	4.05
OZ4	0.267	70		

The effect of exposure to gaseous ozone on strawberries was evaluated using an ozonation system. This consisted of an application chamber with a volume of 15 L and an oxygen gas cylinder with 99% purity, which was connected to an ozone generator, model DCGM-2007/Ecozon® operating on the corona discharge principle according to the specifications of Cavasini (2017).

Before carrying out the tests, the ozonation system was calibrated. This calibration consisted of preparing a solution of potassium iodide at 6.64 g in 2 L of distilled water. In the ozonation system, the ozone flow into the chamber was adjusted to 1 L min^{-1} (LPM) and left on for 2 min. At the same time, the potentiometer was adjusted to 1.6 mg m^{-3}, 4.0 mg m^{-3} and 7.0 mg m^{-3}, and the ozone concentrations obtained were 0.165 mg L^{-1}, 0.267 mg L^{-1} and 0.586 mg L^{-1}. From these results, four treatments were defined for the combination of different ozone concentrations (0.586 mg L^{-1} and 0.267 mg L^{-1}) and exposure times (35 s and 70 s) (Tab. 1). After ozonation, the product was packaged in PET containers and stored at 5±1°C for 5 d, as the fruits showed no signs of damage or visible contamination.

The product was irradiated in a chamber with a wooden structure, lined with aluminum foil and equipped with 12 UV lamps with a wavelength of 254 nm, distributed in the upper and lower parts. The irradiated product was placed at an average distance of 22 cm, with a UV-C light fluence rate of 0.044 W m^2, determined by Souza (2012). The time used for each treatment made it possible to obtain different irradiation energies (Tab. 1). After irradiation, the product was packaged in PET packaging and stored at 5±1°C for 5 d.

For each treatment evaluated, tests for weight loss, color, titratable acidity, soluble solids, pH, and respiration rate were carried out, with three replicates per treatment on days 0, 3, and 5 of storage.

The fruits were weighed on a GEHAKA BG2001 balance, with a minimum load of 2.5 g, a maximum load of 2020 g, and a division of 0.1 g. Weight loss (%) was determined by the difference in mass between the day of the experiment and each day of analysis in the laboratory. The result was expressed as a percentage.

Color was evaluated using the CIELab space, where L* is lightness (0 for black to 100 for white), a* = (-60.0 for green to +60.0 for red), and b* = (-60.0 for blue to +60.0 for yellow). Additionally, the system parameters C* and h° were determined, where C* is the chroma and h° is the hue (Eqs. 1 and 2). Data were collected using a Spectro Photometer CM-700d Konica Minolta colorimeter with a 10° angle and a D65 illuminant in the central area of the fruits. Five replicates were made for each treatment with two readings each on days 0, 3, and 5 of storage.

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (1)$$

$$h^\circ = \arctan\left(\frac{b^*}{a^*}\right) \quad (2)$$

The pH was determined using an ANALION PM 608 digital benchtop pH meter, with the electrode immersed in the product juice until the reading stabilized.

The total soluble solids (TSS) of the strawberries were estimated using an Abbe Mark III automatic Reichert refractometer. The temperature correction value was obtained by placing two drops of distilled water on the instrument lens, followed by the soluble solids value reading, which was taken by placing two drops of sample juice on the lens. The results were expressed in °Brix.

Total titratable acidity (TTA) was calculated according to the methodology developed by Gabriel *et al.* (2015). The results were expressed in mg of citric acid per 100 g. The maturity index was determined as the ratio between TSS and TTA.

The respiration rate was determined using a static system (closed container lid) with an average weight of 100 g in each airtight container. Each of the samples was kept in the refrigerator at a temperature of 5±1°C for 30 min after closing the containers. Gas analysis was carried out using the Mocon Portable Pac Check 325. The results were expressed in mg CO_2 kg^{-1} h^{-1}.

Statistical analysis

The data obtained in the laboratory were subjected to analysis of variance. In addition, the means of each treatment were compared using Tukey's test at 5% probability using the SISVAR 5.6 software.

Results and discussion

During storage, the control treatment showed greater weight loss (7.95%) compared to the gaseous ozone treatments, which showed losses between 4.87% and 6.99%, and the UV-C irradiation treatments, which showed losses between 4.24% and 5.88%. Of the treatments evaluated, the one with the best response was OZ3, with a loss of 4.07%, as shown in Table 2. Strawberry weight loss is an important index that reflects the respiration rate and moisture evaporation between the fruit tissue and the ambient air (Tahir *et al.*, 2018). In addition, strawberries are highly susceptible to rapid water loss due to their extremely thin epidermis (Jiang *et al.*, 2020). The reduction in mass loss during storage is related to the reduction in water loss caused by transpiration and respiration and may also help prevent fruit weakening and shrinkage (Muley & Singhal, 2020).

TABLE 2. Weight loss in strawberries exposed to UV-C radiation and ozone and stored at 5±1°C for 5 d.

Treatment	Day	
	3	5
Control	4.67 ± 0.45 b, B	7.95 ± 1.68 a, C
OZ1	3.11 ± 0.22 ab, B	4.87 ± 0.18 a, C
OZ2	3.41 ± 0.71 ab, B	5.42 ± 1.01 a, C
OZ3	2.37 ± 0.83 a, B	4.07 ± 1.21 a, B
OZ4	3.66 ± 1.34 ab, AB	6.99 ± 3.70 a, B
UVC1	2.83 ± 0.35 ab, B	4.74 ± 0.73 a, C
UVC2	3.14 ± 0.40 ab, B	5.88 ± 0.93 a, C
UVC3	2.36 ± 0.46 a, B	4.24 ± 0.15 a, C

Lowercase letters indicate differences between treatments and uppercase letters indicate differences between analysis days. Same letters do not differ significantly according to the Tukey test (P<0.05). ± indicates standard error (n=5). The treatments are described in Table 1.

Table 3 shows the color parameters of the strawberries on days 3 and 5 of the analysis. On the first day, the color parameters of the strawberries were: L*=50.80 ± 2.46, C*=19.27 ± 3.05, and h°=31.51 ± 5.08 a, A. The treatments that preserved the color of the strawberries, evaluating the parameters of luminosity, chroma, and hue, were OZ1, OZ2, UVC2, and UVC3, as they did not show any significant variation (P>0.05) over the storage period. On day 3, a significant difference (P>0.05) was observed in ozonated strawberries compared to non-ozonated strawberries, indicating that UVC preserved the color of the fruit. This response shows that the treatments with UV-C radiation, UVC2 and UVC3, and the treatments with ozone, OZ1 and OZ2, did not cause significant changes in the color of the strawberries, indicating that the specific concentrations and exposure times did not alter the original characteristics of the fruits.

TABLE 3. Mean values of color characteristics (luminosity L*, chroma C* and hue h°) of strawberries exposed to UV-C radiation and ozone and stored at 5±1°C for 5 d.

Variables	Treatment	Day	
		3	5
L*	Control	48.13 ± 0.94 a, A	48.47 ± 1.09 ab, A
	OZ1	49.01 ± 1.18 ab, A	49.32 ± 1.65 ab, A
	OZ2	48.82 ± 1.57 a, A	48.79 ± 1.25 ab, A
	OZ3	48.96 ± 0.85 ab, AB	48.29 ± 1.42 ab, A
	OZ4	50.31 ± 0.96 b, B	47.70 ± 1.20 a, A
	UVC1	49.01 ± 1.13 ab, AB	48.64 ± 0.79 ab, A
	UVC2	49.25 ± 0.55 ab, A	49.23 ± 1.27 ab, A
	UVC3	49.53 ± 0.93 ab, A	49.68 ± 1.77 b, A
C*	Control	15.97 ± 2.05 a, A	15.22 ± 3.24 a, A
	OZ1	19.52 ± 2.12 b, A	20.55 ± 3.00 b, A
	OZ2	17.84 ± 2.91 ab, A	15.80 ± 4.22 a, A
	OZ3	18.53 ± 2.69 ab, A	17.14 ± 3.71 ab, A
	OZ4	21.04 ± 2.17 b, B	14.90 ± 2.20 a, A
	UVC1	18.76 ± 2.46 ab, AB	15.95 ± 2.62 a, A
	UVC2	18.79 ± 3.06 ab, A	17.74 ± ab, A
	UVC3	18.48 ± 2.28 ab, A	17.05 ± 3.86 ab, A
h°	Control	31.07 ± 3.51 a, A	31.62 ± 3.74 ab, A
	OZ1	28.81 ± 4.61 a, A	29.56 ± 1.92 a, A
	OZ2	30.59 ± 4.39 a, A	30.32 ± 2.24 ab, A
	OZ3	29.55 ± 1.85 a, A	29.88 ± 3.29 a, A
	OZ4	31.75 ± 2.13 a, A	28.77 ± 3.38 a, A
	UVC1	28.42 ± 3.66 a, A	31.17 ± 2.45 ab, A
	UVC2	29.61 ± 3.11 a, A	30.76 ± 4.09 ab, A
	UVC3	31.12 ± 2.77 a, A	34.08 ± 1.66 b, A

Lowercase letters indicate differences between treatments and uppercase letters indicate differences between analysis days. Same letters do not differ significantly according to the Tukey test (P<0.05). ± indicates standard error (n=5). The treatments are described in Table 1.

Luminosity of the fruits was maintained during storage in treatments OZ1, OZ2, UVC2, and UVC3. However, treatments OZ4, OZ3, and the control showed a significant variation (P<0.05) during storage, with the lowest values (47.70, 48.27, and 48.47, respectively) at the end of the treatment. This decrease in luminosity is undesirable during storage, as fruits with intense and bright colors are preferred by consumers (Schifferstein, 2019), and color retention in strawberries during storage is a desired quality attribute (Azam *et al.*, 2019). In general, the luminosity values during storage ranged from 50.8 at the beginning to 47.7 at the end of storage, with a difference of 6.10% for treatments that did not show significant variation. This is a better outcome than that observed by Octavia and Choo (2017), who obtained a variation of 7.14% during storage. However, São José and Vanetti (2015) obtained L* values of 28.45 at the beginning of storage and 19.66 at the end of storage for ultrasound treatments in strawberries, resulting in a 30.9% decrease in fruit brightness. This is unfavorable, as maintaining brightness in strawberries is essential for preserving the quality and appearance of the strawberries. Therefore, the choice of concentrations, exposure times and irradiation energies can influence the preservation of strawberries during storage. UV-C radiation (UVC2 and UVC3) and ozone (OZ1 and OZ2) treatments showed preservation of brightness in strawberries.

During storage, the chroma or color intensity was maintained in treatments OZ1, OZ2, OZ3, UVC2, and UVC3. However, treatments OZ4 and the control showed significant differences (P<0.05) in color saturation of strawberries during storage. Hue did not show significant variation (P>0.05) in all treatments during the storage period. The average hue values remained between 28.77° and 31.51°, with hue values closer to zero for redder fruits and closer to 90° for fruits with a predominance of yellow color. Navas Cajamarca (2015) found that the hue in ozonized strawberries was between 27.51° and 39.03°, which is consistent with the results obtained in this experiment. Treatments that showed significant differences resulted in a decrease in color variables. This is attributed to high exposure doses, which caused changes to the strawberry epidermis, as noted by Macías-Gallardo *et al.* (2023) and Panou *et al.* (2021). Likewise, changes in color could be related to the change in pH and turgor of the fruits, as suggested by Ortiz-Araque (2021).

The pH of the fruits on the first day of analysis was 3.28 ± 0.03. The pH of the stored strawberries showed a decrease of 2.44% in control, a decrease of between 4.78 and 7.83% in the gaseous ozone treatments, and a decrease of between 8.14 and 8.44% in the UV-C radiation treatments. According to the data presented in Table 4, neither the control nor the treatments affected the pH. However, on day 5, the control showed a significant difference (P>0.05) compared to the treatments studied. These significant pH changes during storage may contribute to the accelerated deterioration of strawberries (Cherono *et al.*, 2018; São José & Vanetti, 2015). However, during the analysis period (5 d), no visible changes were observed in the fruits treated with ozone and UV-C radiation that would indicate any surface damage, keeping the strawberries in good storage conditions and demonstrating adequate preservation techniques.

TSS are an indicator of quality and flavor, as they represent the acids, sugars, salts, pectin, and soluble vitamins present in the fruit (Ladika *et al.*, 2024; Yan *et al.*, 2020). On the first day of storage, the total soluble solids had a value of 7.47 °Brix, within the range of 6.8 to 8.7 described by Navas Cajamarca (2015). On days 3 and 5, a decrease in sugar production in strawberries was observed, with values between 9.18 and 14.01 °Brix (Tab.5), within the range found for strawberries by Xie *et al.* (2016). This variable was not affected by treatment exposure, as there were no significant differences (P>0.05). However, significant differences were observed between days 3 and 5 for most treatments (except for treatments OZ3 and OZ4). This significant decrease in TSS during the storage period is possibly related to an improved respiration rate and a less active metabolism in strawberries under refrigerated storage. Similar results were obtained by Mishra and Kar (2014) and Ali *et al.* (2022). As there was no significant variation between treatments, but

TABLE 4. Mean pH values of strawberries exposed to UV-C radiation and ozone and stored at 5±1°C for 5 d.

Treatment	Day	
	3	5
Control	3.24 ± 0.03 a, A	3.20 ± 0.04 b, A
OZ1	3.22 ± 0.05 a, AB	3.12 ± 0.08 ab, A
OZ2	3.21 ± 0.03 a, B	3.05 ± 0.05 a, A
OZ3	3.24 ± 0.07 a, B	3.02 ± 0.02 a, A
OZ4	3.21 ± 0.02 a, B	3.04 ± 0.04 a, A
UVC1	3.19 ± 0.03 a, B	3.01 ± 0.02 a, A
UVC2	3.23 ± 0.04 a, B	3.00 ± 0.06 a, A
UVC3	3.23 ± 0.05 a, B	3.01 ± 0.04 a, A

Lowercase letters indicate differences between treatments and uppercase letters indicate differences between analysis days. Same letters do not differ significantly according to the Tukey test (P<0.05). ± indicates standard error (n=5). The treatments are described in Table 1.

TABLE 5. Mean values of soluble solids content in strawberries exposed to UV-C radiation and ozone and stored at 5 ± 1°C for 5 d.

Treatment	Soluble solids (°Brix)	
	Day	
	3	5
Control	14.01 ± 1.18 a, C	10.98 ± 0.32 a, B
OZ1	13.40 ± 0.69 a, B	9.58 ± 1.79 a, A
OZ2	13.40 ± 1.01 a, B	9.84 ± 2.56 a, AB
OZ3	10.91 ± 3.26 a, A	10.78 ± 0.78 a, A
OZ4	10.83 ± 0.37 a, A	9.83 ± 2.41 a, A
UVC1	11.05 ± 0.69 a, AB	9.18 ± 1.17 a, B
UVC2	10.75 ± 0.50 a, B	11.25 ± 1.10 a, B
UVC3	11.51 ± 0.39 a, B	9.45 ± 1.99 a, AB

Lowercase letters indicate differences between treatments and uppercase letters indicate differences between analysis days according to the Tukey test (P<0.05). ± indicates standard error (n=5). The treatments are described in Table 1.

a significant decrease between storage days, this suggests that storage temperature may have influenced and slowed down the metabolic changes in the fruit. This behavior was also observed by Ladika *et al.* (2024), who attributed the decrease in TSS to the low and controlled temperature in a refrigerated environment, which helped extend the shelf life of the strawberries.

As shown in Table 6, the TTA of the strawberry treatments ranged from 0.99 to 1.04 mg citric acid 100 g^{-1}. The TTA obtained on the first day of the analysis was 1.01 ± 0.08. These obtained values are consistent with those reported by Liu *et al.* (2018). The total titratable acidity did not show significant differences (P>0.05) in the treatments evaluated during the storage period. This behavior can be attributed to the fact that strawberries are non-climacteric fruits and do not undergo drastic biochemical changes after harvesting (Alvarado-Cepeda *et al.*, 2020).

Likewise, the applied treatments suggest that none significantly affected titratable acidity, in accordance with Ali *et al.* (2022) and Mussin *et al.* (2014). When compared with the results obtained by Chen *et al.* (2020) on cantaloupe melons exposed to different doses of ozone, they found that the delayed loss of TTA values is associated with the metabolic activity and respiration rates of the fruits and can be attributed to the action resulting from ozone exposure. Another contributing factor could be the suitable storage conditions, as discussed by Ali *et al.* (2022), Ladika *et al.* (2024), and Yan *et al.* (2020).

TABLE 6. Mean values of titratable acidity and maturity index of strawberries exposed to UV-C radiation and ozone and stored at 5±1°C for 5 d.

Treatment	Titratable acidity (mg citric acid 100 g^{-1})	Maturity index
	Day	Day
	5	5
Control	1.03 ± 0.03 a, A	10.70 ± 0.59 a, B
OZ1	1.02 ± 0.05 a, A	9.41 ± 1.68 a, A
OZ2	1.02 ± 0.02 a, A	9.72 ± 2.69 a, A
OZ3	1.03 ± 0.01 a, A	10.51 ± 0.80 a, B
OZ4	1.04 ± 0.06 a, A	9.50 ± 2.73 a, A
UVC1	0.99 ± 0.05 a, A	9.34 ± 1.59 a, A
UVC2	1.03 ± 0.09 a, A	11.05 ± 2.09 a, B
UVC3	1.04 ± 0.04 a, A	9.11 ± 1.76 a, A

Lowercase letters indicate differences between treatments and uppercase letters indicate differences between analysis days according to the Tukey test (P<0.05). ± indicates standard error (n=5). The treatments are described in Table 1.

The maturity index of the strawberries on the first day of analysis was 7.44±0.45. Table 6 shows the 5-d maturity index, and this parameter was higher on the fifth day of storage for both the control and the evaluated treatments. However, the control and the UVC2 treatment presented a higher TSS/TTA ratio, indicating that the product underwent a more accelerated maturation process than the products subjected to the other treatments. The treatment with the lowest maturity index was UVC3. It is possible to conclude that the treatments had no effect on this variable, since they did not show a significant difference. However, the duration of storage affects the response of the control and the OZ3 and UV-C treatments. The values obtained for the TSS/TTA ratio are similar to those reported by Alves *et al.* (2019).

Due to their high respiration rate, strawberries are susceptible to water loss, mechanical damage, and fungal spoilage, which may result in a short postharvest shelf life (Liu *et al.*, 2018; Pott *et al.*, 2020). In general, the respiration rate of strawberries ranges between 18.37 and 22.69 mg CO_2 kg^{-1} h^{-1}, which agrees with Cunha Junior *et al.* (2011) and Zhang *et al.* (2020), who obtained similar respiration rates. The respiration rate on the first day of analysis was 21.68±0.96 mg CO_2 kg^{-1} h^{-1}. The control treatment showed a significant variation (P<0.05) with respect to both factors (storage time and treatments). Table 7 shows that the OZ3 and UVC3 treatments presented a significant decrease (P<0.05) during the first three days of storage due to two factors: the cold environment and the effect of exposure to the OZ3 and UVC3 treatments, which reduced the respiration rate of the product until day 3. The significant increase observed in the control treatment indicates that the UV-C and ozone treatments were effective in slowing down the respiration rate of the treated fruits, which positively contributes to preserving their quality and extending their shelf life, consistent with the findings of Ali *et al.* (2022).

This behavior was also observed by Cunha Junior *et al.* (2011), who reported a reduction from 21.8 to 10.83 mg CO_2 kg^{-1} h^{-1} in strawberries exposed to a controlled atmosphere with different O_2 concentrations during the first 3 d, after which the concentrations remained stable until the end of the experiment. By not allowing the respiration rate to increase significantly, relevant changes in the fruit components, which could be undesirable from a quality standpoint, are avoided. For this reason, the treatments used proved to be effective in preventing a significant increase in the respiration rate of the strawberries.

TABLE 7. Mean values of respiration rate in strawberries exposed to UV-C radiation and ozone and stored at 5±1°C for 5 d.

Treatment	Respiration rate [mg CO_2 kg^{-1} h^{-1}]	
	Day	
	3	5
Control	20.93 ± 1.10 ab, A	22.69 ± 1.03 b, A
OZ1	20.26 ± 0.36 ab, A	20.82 ± 0.91 ab, A
OZ2	21.82 ± 1.05 b, A	22.03 ± 0.94 ab, A
OZ3	18.37 ± 0.53 a, A	20.44 ± 0.67 a, B
OZ4	20.41 ± 0.48 ab, A	21.85 ± 0.65 ab, A
UVC1	19.36 ± 1.40 ab, A	21.97 ± 0.10 ab, B
UVC2	19.41 ± 1.36 ab, A	22.08 ± 0.57 ab, B
UVC3	19.84 ± 0.19 ab, A	21.07 ± 0.39 ab, AB

Lowercase letters indicate differences between treatments and uppercase letters indicate differences between analysis days according to the Tukey test ($P<0.05$). ± indicates standard error (n=5). The treatments are described in Table 1.

Conclusions

Strawberries exposed to UV-C radiation and ozone performed better than the control treatment kept at 5±1°C during storage, demonstrating the benefits of these preservation techniques on the physicochemical characteristics of the product. However, the best results were obtained with the OZ3 (higher concentration and shorter exposure time) and UVC3 treatments. These doses were sufficient for the conservation of strawberries under natural conditions. Conversely, low ozone concentrations were not favorable for the natural preservation of strawberries, regardless of the exposure time.

Experimental tests to analyze the physicochemical characteristics of strawberries, such as weight loss, color, pH, TSS, TTA, maturity index and respiration rate, proved to be adequate indicators for assessing their quality. However, it is recommended that tests be conducted over extended periods and with varying doses to establish the optimal concentration range for the proper preservation of strawberries.

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Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author's contributions

JAJM: methodology, data curation, formal analysis, research, writing – original draft. ELHC: methodology, data curation, formal analysis, research, writing – original draft. RMA: conceptualization, methodology, data curation, writing – review & editing. CMSS: conceptualization, methodology, writing – review & editing, supervision. FCSU: conceptualization, methodology, writing – review & editing, resources, supervision. All authors approved the final version of the manuscript.

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