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UV-C light effects on physicochemical and microbiological characteristics of Cape gooseberry (*Physalis Peruviana* L.)

Efecto de UV-C en las características fisicoquímicas y microbiológicas de la uvilla (*Physalis Peruviana* L.)

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Hongo, química agrícola, conservación de los alimentos, tecnología alimentaria, recursos alimentarios

ABSTRACT: The effect of UV-C light radiation on the physicochemical and microbiological properties of Cape gooseberry (*Physalis peruviana* L.) fruits was studied. UV-C treatment was applied for different exposure times (7, 10, and 13 minutes) and fruits were stored at both refrigeration (5 ± 1°C) and room temperature (24 ± 1°C). Results showed that a 7-minute UV-C treatment was most effective in delaying fungal growth while preserving the quality of the fruit. However, higher exposure times led to increased weight loss and did not significantly inhibit fungal development. The study suggests UV-C light as a potential conservation method for extending the shelf life of Cape gooseberry without significantly affecting its quality parameters, though caution is needed regarding exposure times due to potential adverse effects on the cuticle and waxes of the fruit.

RESUMEN: Se analizó el efecto de la radiación de luz UV-C sobre las propiedades fisicoquímicas y microbiológicas de los frutos de uvilla (*Physalis peruviana* L.). Se aplicaron tratamientos con UV-C durante diferentes tiempos de exposición (7, 10 y 13 minutos) y los frutos se almacenaron tanto a temperatura de refrigeración (5 ± 1 °C) como a temperatura ambiente (24 ± 1 °C). Los resultados mostraron que el tratamiento con UV-C durante 7 minutos fue el más eficaz para retrasar el crecimiento fúngico mientras se mantenía la calidad del fruto. Sin embargo, tiempos de exposición más prolongados provocaron un mayor porcentaje de pérdida de peso y no inhibieron significativamente el desarrollo fúngico. El estudio sugiere que la luz UV-C podría ser una estrategia de conservación viable para extender la vida útil de la uvilla sin afectar significativamente sus parámetros de calidad, aunque es importante

tener cuidado con los tiempos de exposición debido a posibles efectos adversos sobre la cutícula y las ceras epicuticulares del fruto.

1. Introduction

Cape gooseberry, also known as *Physalis peruviana*, is an exotic tropical fruit native to the Andean region, particularly cultivated in countries such as Colombia, Peru, and Ecuador [1]. Recent attention has been drawn to its health benefits and economic potential [2]. *Physalis peruviana* is rich in health-related compounds such as anti-inflammatory agents and has antioxidant activities; it is also endowed with a nutritional profile high in vitamins A, B, and C, and essential minerals [3,4]. Cape gooseberry contains sugars such as sucrose, fructose, and glucose, as well as organic acids such as citric, malic, and tartaric [5]. Compared to other fruits, Cape gooseberries carry higher levels of protein and phosphorus [1]. The production and commercial potential of the fruit are linked to its quality attributes, making it attractive to various international markets [6]. However, Cape gooseberries are highly perishable, leading to degradation reactions affecting their sensory and nutritional qualities and shelf life [7]. To address this, non-thermal technologies such as UV radiation have emerged as viable options for prolonging shelf life while maintaining its quality [8]. UV-C radiation has gained attention for its effectiveness in deactivating microorganisms [9]. UV-C irradiation causes physical modifications in DNA, inhibiting microbial development [10]. This technology is cost-effective and environmentally friendly [11]. UV-C treatment induces the production of antimicrobial compounds, slows ripening, and triggers the accumulation of beneficial substances [12]. However, the sensitivity of fruit tissues to UV-C treatment varies, and high doses may lead to oxidation of bioactive substances and superficial darkening. *Physalis peruviana* is considered a functional food due to its nutritional properties and bioactive components, which include vitamin C, vitamin E, and phenolic compounds [13]. The germicidal action of UV-C light peaks around 254 nm and decreases significantly beyond that range [14]. Various microbial groups, including bacteria, viruses, yeasts, and fungi, are affected by UV-C irradiation [15]. The required dosage for microbial inactivation depends on factors such as the nature of the microorganism and the application surface [16]. Given the potential of UV-C light as a preservation technology, this study examines the impact of different exposure times on the physicochemical and microbiological characteristics of Cape gooseberry (*Physalis peruviana* L.), evaluating how these factors affect the shelf life and quality of the fruit. Subsequently, the methods of UV-C light application, the quality parameters analysed, and the results obtained are discussed, with the aim of establishing guidelines for its possible implementation in the food industry.

2. Material and methods

2.1. Raw material

Physalis peruviana L. fruits were sourced from a farm in Chilla, El Oro, Ecuador. To ensure a homogeneous sample set and minimise variability, fruits were chosen based on criteria such as soluble solids content, size, and shape. Fruit size ranged approximately between 2.0 and 3.0 cm diameter, 3.5 ±

0.5 pH and 13 ± 1.0 °Brix. Prior to their analysis, fruits were stored under refrigeration at 5 ± 1 °C until 1 h before the laboratory study.

2.2 Equipment description

A UV-C sealed light chamber (40cm × 30cm × 100cm) featuring six germicidal lamps emitting primarily at 253.7 nm was used. This chamber consisted of two lamps, TUV-15W and G15 T8 (Koninklijke Philips N.V., Amsterdam, The Netherlands) positioned at the top and bottom, respectively, along with two lateral lamps, TUV-6W and G6 T5 (Koninklijke Philips N.V., Amsterdam, The Netherlands). Fruits were placed in a polyethylene plastic basket affixed to a wooden frame positioned 13.5 cm below the upper lamps and equidistant from the lower lamps, with 25 cm distance on each side from the lateral lamps. To assure uniform UV-C irradiation across the surface of the fruits, the polyethylene basket was made with a mesh sheet. To enhance the reflective properties, the internal lining of the chamber consisted of aluminium foil. An extraction fan VF-N4 (Eason Electricals Co., Ltd., Guangdong, China) was incorporated to avoid fruit overheating during UV-C radiation. Initially the fruit was at room temperature 25 ± 1°C. The maximum temperature reached after UV-C treatments was 33 ±1°C. UV-C lamps were turned on 30 min before use to ensure their stabilization.

2.3 UV-C light exposure times and storage of treated fruits

UV-C radiation exposure times were determined based on prior research involving similar fruits [17, 18]. Fruits were irradiated for 7, 10, and 13 minutes (UV-C 7 min, UV-C 10 min, UV-C 13 min, respectively). Irradiated fruits were contrasted against control samples (fresh fruit FF, unexposed to UV-C light). UV-C treated fruit and control were packed in closed air permeable polypropylene boxes and stored at 5 ± 1°C and 24 ± 1°C (room temperature). The storage time was 36 days (refrigerated) and 18 days (room temperature) for microbiological assessments and 15 to 30 days (room and refrigerated temperature, respectively) for physicochemical analyses. Throughout the storage period, relative humidity was maintained at 90% using a PM6252B precision humidity meter (Peakmeter, Shenzhen, China).

2.4 Determination of microbial growth in Cape gooseberry fruits

Fungal decay was monitored daily through visual inspection over a period of 36 days (refrigerated) and 18 days (room temperature). Each condition was assessed using 60 fruits, arranged in 3 trays (replicates) containing 20 fruits each. Infected fruits were identified based on the presence of visible macroscopic mycelial growth, regardless of the extent of infection. Results were expressed as percentage of decayed fruit according to Equation 1:

$$DF(\%) = \frac{f_t}{f_0} \times 100 \qquad (1)$$

Where:
DF (%) = Percentage of decayed fruits
f_o = Initial number of fresh fruits
f_t = Number of decayed fruits at time *t*.

For the microbiological analysis, refrigerated fruits were stored at 5 ± 1°C for 30 days, then at 24 ± 1°C (room temperature) for 6 more days to emulate distribution to consumers, totalling 36 days. The condition

mentioned here refers to a separate group of fruits, distinct from those evaluated solely at room temperature.

2.5 Assessment of quality parameters

2.5.1 Total soluble solids, titratable acidity, and pH

Soluble solids (SS) content was assessed with the help of a HI 96801 digital refractometer (HANNA instruments, Padovano, Italy). The pH measurements were conducted using a Bante900P pH meter (Bante Instruments, Shanghai, China). Titratable acidity (TA) was determined following the potentiometric titration method (AOAC, 2005): a 5 g sample was mixed with 50 mL of distilled water at 80°C and allowed to settle for 30 minutes. Pulp was separated from the solution using sterile gauze. Samples were titrated with a NaOH 0.1N solution and using phenolphthalein to denote the end point (pH = 8.2 ± 0.1). Those results were expressed as grams of citric acid per 100 g fruit pulp (% w/w) according to Equation 2. All measurements were performed in triplicate at 25 ± 1°C.

$$\%Acidity = \frac{V_{NaOH} \times N_{NaOH} \times P_{meqcitricacid}}{P_{sample}} \times 100 \qquad (2)$$

where:
V_{NaOH} = volume of NaOH used to reach 8.2 ± 0.1 pH (mL)
N_{NaOH} = NaOH normality (0.1 N)
$P_{meq\ citric\ acid}$ = milliequivalent weight of citric acid (0.064)
P_{sample} = sample weight (g).

2.5.2 Determination of weight loss

Untreated and treated Cape gooseberry fruits were weighed on days 0, 5, 10, 15, 20, and 25 of storage at 5 ± 1 °C using a high-precision balance HR-250AZ (A&D Company, Tokyo, Japan) with a ± 0.0001 g accuracy. Due to the evident microbiological occurrence, fruits stored at room temperature were monitored until day 15. Results were expressed as percentage of weight loss compared with the initial weight of fresh and irradiated samples on day 0, according to Equation 3.

$$WL(\%) = \frac{(W_0 - W_t)}{W_0} \times 100 \qquad (3)$$

where:
WL (%) = percentage of weight loss of the sample
w_0 = initial sample weight at day 0
w_t = sample weight at time t.

2.5.3 Extraction of bioactive compounds

The extraction of bioactive products from the Cape gooseberry fruits was carried using the ratio of 5 g of crushed fruits in 50 mL of the ethanol-water mixture (80:20 v/v). Extraction took place in an ultrasound bath at 40 kHz (Fischer Scientific, Hampton, United States) for 30 min at room temperature. The resulting extract was filtered through a filter paper #1 (Whatman International Ltd, Kent, United Kingdom). The extracts obtained were concentrated to dryness using an evaporator Laborota 4001 (Heidolph Instruments

GmbH & Co. KG, Schwabach, Germany) at 40°C, coupled to a RA-8 cryostat (Lauda Dr. R. Wobser GmbH & Co. KG, Lauda-Königshofen, Germany) and a vacuum pump PC 600 (Vacuubrand GmbH + Co KG, Wertheim, Germany). The dry extracts (DE) were stored at 5°C and protected from light until further analysis. The determination of total phenolic and antioxidant capacity (TEAC) was carried out in hydroalcoholic solutions prepared with DE (0.05 mg/mL). All measurements were performed in triplicate for each condition.

2.5.4 Determination of total phenolics after the Folin-Ciocalteu method

To determine the total phenolics after the Folin Ciocalteu method, the protocol previously described in the literature was used [19], with minor modifications. The absorbance of the samples was read at 765 nm, using 2 mL microcells and a UV-visible spectrophotometer Evolution 201 (Thermo Scientific, Waltham, United States). The quantification of total phenols was carried out using a calibration curve determined with gallic acid (Sigma-Aldrich, Saint Louis, United States) at concentrations of 0.1, 0.3, 0.5, 0.7, and 0.9 mg/mL, from which, through a linear regression analysis (R^2 = 0.9997), the Equation 4 was obtained. All samples were analysed in triplicate and the results were reported as milligram equivalents of gallic acid per gram of DS (mg GAE/g DS).

$$Absorbance = 1.0106X + 0.0195 \times concentration(\frac{mg}{mL}) \quad (4)$$

2.5.5 Trolox equivalent antioxidant capacity (TEAC) by the DPPH method

The evaluation of antioxidant capacity (AC) followed methodologies previously described in the literature [20], with some modifications. 200 µL of the hydroalcoholic extract was mixed with 3.8 mL of the ethanolic solution of DPPH (0.1 mM). The DPPH control was prepared by combining 200 µL of absolute ethanol with 3.8 mL of DPPH solution (0.1 mM). The reaction mixture was stirred for 30 seconds and allowed to settle at room temperature and protected from light. Absorbance readings were taken at 517 nm using a Spectronic 20 Genesys spectrophotometer (SpectraLab Scientific Inc., Markham, Canada). An 80% (v/v) ethanol solution served as the blank for the spectrophotometer readings. The AC of the samples was calculated using Equation 5 and expressed as milligrams of trolox equivalent per gram of DE (mg ET/g DE). Measurements were performed in triplicate for each condition, and each extract was analysed in duplicate, reporting the mean and standard deviation. Solutions of trolox (6-hydroxy-2,5,7,8 tetramethylchroman-2-carboxylic acid) ranging from 0.02 to 0.2 mg/mL were used to obtain the calibration curve (R^2 = 0.9912).

$$h = 308.13 \times concentration\left(\frac{mg}{mL}\right) - 3.6507 \quad (5)$$

2.5.6 Trolox equivalent antioxidant capacity (TEAC) by the FRAP method

The determination of this parameter was carried out according to methodologies previously described in the literature [21]. The calibration curve was prepared with trolox dissolved in ethanolic solutions, employing absolute ethanol for the analysis. (Panreac Applichem, ITW Reagents, S.R.L., Monza, Italy), in concentrations from 0.02 to 0.2 mg/mL. For the assay, 50 µL of the standard or sample was mixed with 1.5 mL of the FRAP reagent, which was previously prepared. Readings at 593 nm were carried out in 2 mL-plastic-microcells after 5 minutes and the FRAP solution was used as a blank. The result was

expressed as trolox equivalent (TEAC) per gram of DE (TEAC/g DE), using Equation 6, which was obtained from the following linear regression analysis (R^2 = 0.9933):

$$Absorbance = 5.2994X - 0.0364 \times concentration\left(\frac{mg}{mL}\right) \quad (6)$$

2.6 Statistical analysis

The results were expressed as the mean ± standard deviation and analysed using the statistical software Infostat v.2020e (National University of Córdoba, Córdoba, Argentina). A two-way analysis of variance (ANOVA) was used to compare the effect of the UV-C treatment and the storage time on the data obtained for native microbiota, titratable acidity (TA), pH, soluble solids, antioxidant capacity, and total phenols. Afterwards, mean values were compared by the Tukey's test. The significance level was set at 0.05. Prior to conducting the analyses, assumptions of normal distribution and homogeneous variance among groups were verified. In some cases, data transformation to square root was necessary to meet said assumptions.

3. Results and discussion

3.1. Evolution of native microbiota in fruits treated with UV-C light and stored at refrigeration temperature

The efficacy of UV-C light treatment in Cape gooseberry stored at 5°C is shown in Figure 1. Fungal proliferation was evident primarily around the peduncle insertion area, with minimal occurrence elsewhere on the fruit. The ANOVA indicated that the main effects 'treatment' and 'storage time' were significant ($F_{3, 48} = 25.05$; $p < 0.000$ and $F_{5, 48} = 59.34$; $p < 0.000$, respectively); no significance was shown over their interaction ($F_{15, 48} = 1.43$; $p = 0.1737$). The findings indicate that not all UV-C treatments showed an inhibitory effect on mould growth compared to control fruit (FF). The percentage of infected fruit in irradiated Cape gooseberry for 7 min was significantly lower than control and other UV-C treatments during storage days. In addition, irradiated samples for 7 min presented a delay on the onset of infection of 2 days when compared to FF. At 20 days of storage, all samples exhibited the onset infection; however, samples irradiated for 7 min presented fungal decay at 22 days. When fruits were treated for 10 and 13 min of UV-C light, fungal decay was greater in the irradiated samples. Despite both the irradiated and control samples showing higher percentages of infected fruit during storage, the fungal decay occurrence was notably lower in the fruit treated with UV-C 7 min. The accelerated fungal incidence observed in both control and treated fruits after 30 days of storage can be attributed to changes in storage temperature.

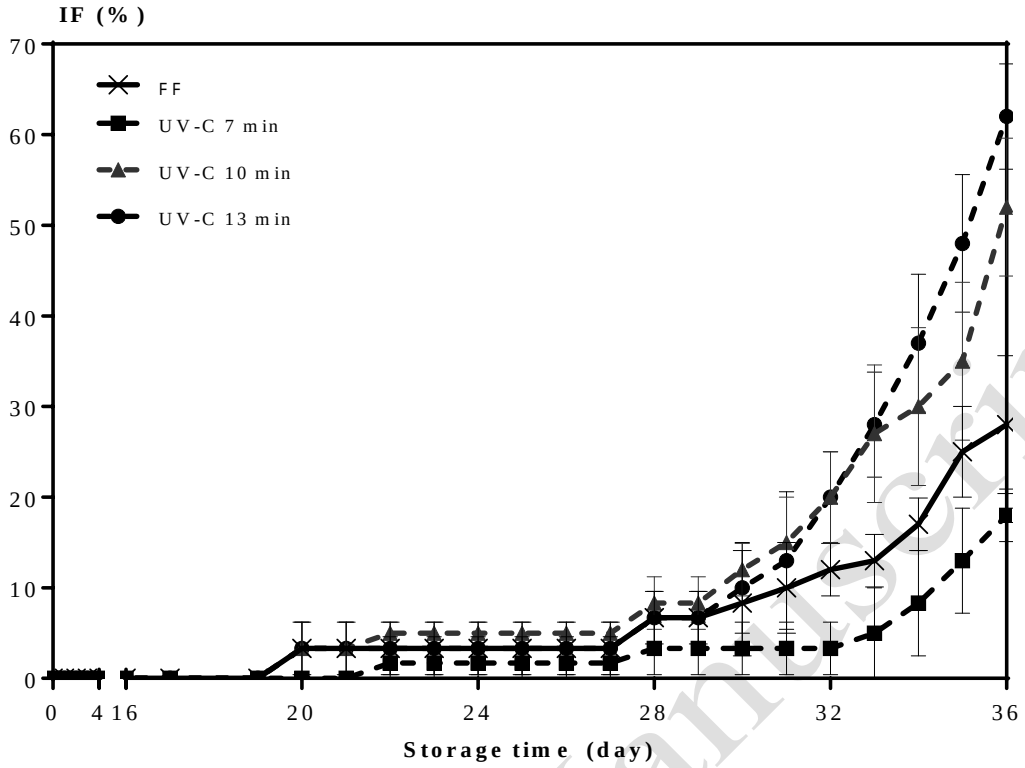

Figure 1. IF (%) of native microbiota in Cape gooseberry exposed to different UV-C radiation times and stored at 5 ± 1 ºC for 36 days. Vertical bars represent standard deviations

3.2 Evolution of native microbiota in fruits treated with UV-C light and stored at room temperature

Fungal development in treated and untreated stored Cape gooseberry under the storage conditions mentioned is shown in **Figure 2**. No significant interaction between treatment and storage time factors ($F_{12, 40} = 1.30$; $p = 0.2577$) were observed, whereas main effects of each factor were statistically significant ($F_{3, 40} = 25.05$; $p < 0.0001$, $F_{4, 40} = 55.37$; $p < 0.0001$, respectively).

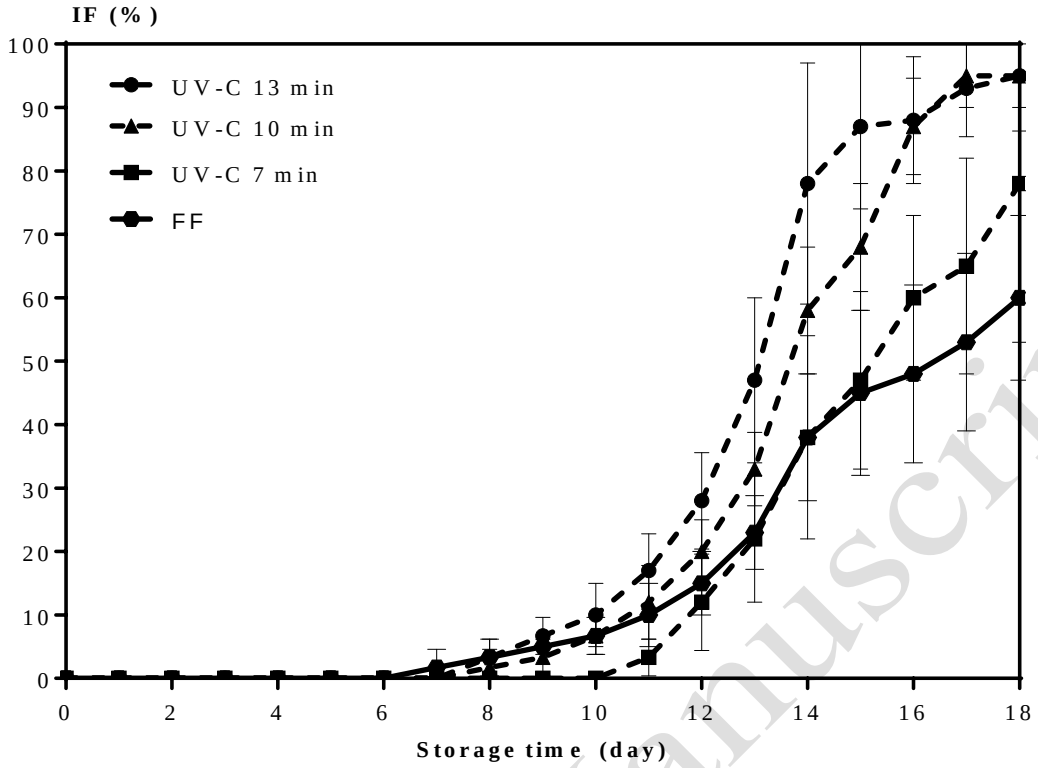

Figure 2. IF (%) of native microbiota in Cape gooseberry exposed to different UV-C radiation times and stored at 24 ± 1 ºC for 18 days. Vertical bars represent standard deviations.

A two-factor ANOVA was performed to identify potential differences between UV-C treated samples and controls stored at room temperature. To meet residual normality and homoscedasticity assumptions between treatments, transformation of data to their square root form was undertaken. The statistical analysis did not reveal interactions between treatment and storage time factors ($F_{12, 40} = 1.30$; $p = 0.2577$). Based on the results of this study, a comparison between irradiated and control samples revealed that the UV-C 7min exposure resulted in a significantly lower average percentage of infected fruits compared to the control group. On the other hand, fungal decay in samples irradiated for 10 and 13 minutes was significantly higher compared to the control and UV-C 7 min fruit. The delay on the onset of infection compared with the control was 4 days for irradiated samples with UV-C 7 min treatment. As the percentage of infected fruits increased with the extended storage duration across all tested conditions and analysed storage periods, significant differences were observed ($F_{4, 40} = 55.37$; $p < 0.0001$). The discernible disparity in fungal infection percentage after 30 days of storage between samples stored at refrigeration and room temperature marks the combined inhibitory effects of UV-C treatment (particularly at 7 minutes) and low-temperature storage, thus extending the shelf life of the fruits. The results obtained for samples treated with UV-C for 10 and 13 minutes could be strongly associated with modifications induced by UV-C radiation in the epicuticular waxes and the cuticle of the studied fruits. In comparison with the literature, previous studies on blueberries indicated that the UV-C treatment can induce alterations and redistribution of waxes on the fruit surface [11]. The role that epicuticular waxes play in prevention of fungal infection in fruits has been well-established [22, 23, 24], as well as the inhibitory effects of post-harvest UV-C treatments on various fruits, including tomatoes, pineapples, blueberries, strawberries, Cape gooseberries, papayas, and others [10, 11, 25]. Regarding Cape

gooseberries, findings similar to those in the present work showed that lower UV-C doses inhibited mould and yeast growth during storage, whereas higher doses actually increased microbial proliferation compared to the control. [26]. The impact of UV-C light (0, 8, 12.5 kJ/m²) on Cape gooseberry, lulo (*Solanum quitoense*) and Andean blueberry (*Vaccinium floribundum*) over 21 days at 6°C was evaluated [25] and the pertinent findings partially align with those in this works, indicating that the doses tested effectively mitigated microbial spoilage across all fruits, with the highest dose being the most effective. It is worth noting that the impact of UV-C light on the native microbial flora differs from its effects on specific microorganisms. This discrepancy may be attributed to various factors, including the tested doses, irradiation mode (batch, continuous), environmental and geographical conditions, crop type, and harvest season.

3.3 Titratable acidity, pH, and soluble solids content of UV-C treated fruits at refrigeration and room temperature

A two-factor analysis of variance (ANOVA) was conducted for all evaluated parameters to discern significant differences between treated samples and the control. The statistical analysis showed no interaction between the treatment and the storage time for titratable acidity and soluble solids content ($F_{15, 48} = 1.13$; $p = 0.3542$, $F_{15, 48} = 0.86$; $p = 0.6061$, respectively). Overall, no significant differences were found in SS values either due to irradiated treatment ($F_{3, 48} = 2.76$; $p = 0.052$) or storage day. At day 25, however, a significant increase ($F_{3, 48} = 20.02$; $p = 0.0001$) in SS content was observed in all samples assayed. TA values in irradiated samples did not significantly differ from those of the control fruits ($F_{3, 48} = 1.66$; $p = 0.1892$). During storage, both treated and control fruits exhibited did not significantly decrease during the first 10 days. However, on day 15, both treated and control samples experienced a significant decrease in TA values ($F_{3, 48} = 23.47$; $p < 0.001$). The pH values showed an interaction between the treatments and the storage time ($F_{15, 48} = 2.2$; $p = 0.0197$). Generally, for the same storage day, the behaviour of treated and untreated samples was similar. When comparing different storage days, the pH of all samples showed a low significant increased after 10 days of storage. Regarding soluble solids content (SS, °Brix), no significant differences were observed overall ($F_{3, 48} = 2.76$; $p = 0.052$) in the values of UV-C treated samples compared to control fruits, except for fruits irradiated for 13 minutes, which showed slightly but significantly higher values than the control. During storage, SS values up to day 20 showed no significant difference. However, on day 25, a significant increase ($F_{3, 48} = 20.02$; $p = 0.0001$) in SS content was observed in all tested treatments. Titratable acidity (TA) values in irradiated samples did not significantly differ from control fruits ($F_{3, 48} = 1.66$; $p = 0.1892$). During storage, TA did not significantly decrease during the first 10 days. However, on day 15, both treated and control samples exhibited a significant decrease in TA values ($F_{3, 48} = 23.47$; $p < 0.001$). Table 1 depicts the results for soluble solids (SS, ºBrix), titratable acidity (% w/w citric acid), and pH in fresh (control) and UV-C treated Cape gooseberries stored at 5 ± 1ºC for 25 days. Results are presented as mean ± standard deviation. Values in the same column with the same lowercase letter indicate no significant differences ($p < 0.05$) between treatments. Values with the same uppercase letter indicate no significant differences ($p < 0.05$) between storage days. The letters in the pH values reflect the interaction between treatment and storage duration.

Table 1 SS (ºBrix), acidity (% w/w), and pH in fresh (control) and UV-C treated Cape gooseberries stored at 5 ± 1ºC for 25 days

Day	Treatment	SS (°Brix)	Acidity (%)	pH
0	Control	13.0±0.3^{a,A}	1.5±0.04^{a,A}	2.9±0.0^{a}
	UV-C 7 min	13.6±0.6^{a,b,A}	1.5±0.08^{a,A}	3.0±0.1^{a}
	UV-C 10 min	13.3±0.2^{a,b,A}	1.5±0.09^{a,A}	3.2±0.1^{a}
	UV-C 13 min	13.8±0.5^{b,A}	1.5±0.03^{a,A}	3.0±0.1^{a}
5	Control	13.7±0.7^{a,A}	1.5±0.08^{a,A}	3.8±0.1^{b,c}
	UV-C 7 min	13.4±0.9^{a,b,A}	1.5±0.04^{a,A}	3.7±0.1^{b,c}
	UV-C 10 min	13.0±0.5^{a,b,A}	1.5±0.07^{a,A}	3.8±0.1^{b}
	UV-C 13 min	13.2±0.8^{b,A}	1.5±0.01^{a,A}	3.7±0.1^{b}
10	Control	13.1±0.6^{a,A}	1.5±0.05^{a,A}	4.0±0.1^{b,c}
	UV-C 7 min	13.3±0.4^{a,b,A}	1.5±0.07^{a,A}	3.8±0.1^{b,c}
	UV-C 10 min	13.3±0.7^{a,b,A}	1.6±0.03^{a,A}	3.7±0.1^{b,c}
	UV-C 13 min	13.6±0.2^{b,A}	1.5±0.02^{a,A}	3.8±0.1^{b,c}
15	Control	13.8±0,7^{a,A}	1.3±0.02^{a,B}	3.8±0.1^{b,c}
	UV-C 7 min	13.8±0,7^{a,b,A}	1.3±0.04^{a,A}	4.0±0.1^{b,c}
	UV-C 10 min	13.8±0,8^{a,b,A}	1.4±0.10^{a,B}	4.0±0.1^{b,c}
	UV-C 13 min	14.1±0,6^{b,A}	1.4±0.03^{a,B}	3.8±0.0^{b,c}
20	Control	13.2±0.4^{a,A}	1.3±0.15^{a,B}	3.8±0.0^{b,c}
	UV-C 7 min	13.1±0.2^{a,b,A}	1.3±0.06^{a,B}	4.0±0.1^{b,c}
	UV-C 10 min	13.5±0.7^{a,b,A}	1.3±0.04^{a,B}	4.1±0.0^{c}
	UV-C 13 min	14.4±0.8^{b,A}	1.4±0.09^{a,B}	4.0±0.2^{b,c}
25	Control	14.7±0.3^{a,B}	1.4±0.10^{a,B}	3.8±0.1^{b,c}
	UV-C 7 min	15.3±0.1^{a,b,B}	1.3±0.04^{a,B}	3.9±0.0^{b,c}
	UV-C 10 min	15.6±0.8^{a,b,B}	1.4±0.09^{a,B}	3.9±0.0^{b,c}
	UV-C 13 min	15.6±0.1^{b,B}	1.3±0.10^{a,B}	3.9±0.1^{b,c}

The two-factor analysis of variance (ANOVA) conducted for titratable acidity, pH, and soluble solids content of UV-C treated and untreated fruits at room temperature showed no interaction between the treatment and the storage time for soluble solids content, titratable acidity, and pH ($F_{9, 32} = 2.12$; $p = 0.0577$, $F_{9, 32} = 1.38$; $p = 0.2395$, $F_{9, 32} = 0.63$; $p = 0.7611$, respectively). In SS content, any significant differences among treated and control fruits were observed ($F_{3, 32} = 3.04$, $p = 0.0429$). Throughout the storage period, SS values remained relatively stable at day 0, but from day 5 onwards, a significant increase was observed in the SS content of all evaluated samples ($F_{3, 32} = 18.51$, $p = 0.9107$), and after 15 days storage, this increase was even more pronounced. TA values in the irradiated samples did not show significant differences compared to the control fruits ($F_{3, 32} = 0.04$; $p = 0.988$). During the storage period, TA values did not exhibit a significant decrease during the initial 10 days; in contrast, by day 15, both the treated and control samples showed a significant decreased ($F_{3, 32} = 28.57$; $p < 0.001$). pH values in both control and irradiated samples did not exhibit significant differences ($F_{3, 32} = 0.18$; $p = 0.9107$). However, during storage, all samples showed a significant increase in pH values ($F_{3, 32} = 20.56$; $p < 0.001$). These results suggest that UV-C treatment, whether applied to refrigerated or room temperature stored samples, did not induce adverse changes in these quality fruit attributes. The observed changes in SS, TA, and pH values, under both storage temperature, were consistent with the natural

ripening process of the fruit, characterised by a gradual increase in pH and a decrease in TA due to the breakdown of organic acids and the conversion of sugars to simpler forms, resulting in a fruit with a less acidic and sweeter taste. The results for soluble solids (SS, ºBrix), titratable acidity (% w/w citric acid), and pH in fresh (control) and UV-C treated Cape gooseberries stored at 24 ± 1ºC for 15 days are arranged and depicted in **Table 2**. Results are expressed as mean ± standard deviation. Values within the same column identified with the same lowercase letter indicate no significant differences ($p < 0.05$) between treatments; values with the same uppercase letter indicate no significant differences ($p < 0.05$) between storage days.

Table 2. SS (ºBrix), acidity (% w/w), and pH of fresh (control) and UV-C treated Cape gooseberries stored at 24 ± 1ºC for 15 days

Day	Treatment	SS (ºBrix)	Acidity (%)	pH
0	Control	$12.9\pm0.1^{a,A}$	$1.56\pm0.08^{a,A}$	$3.67\pm0.1^{a,A}$
	UV-C 7 min	$13.4\pm0.1^{a,A}$	$1.48\pm0.13^{a,A}$	$3.67\pm0.1^{a,A}$
	UV-C 10 min	$12.9\pm0.1^{a,A}$	$1.50\pm0.10^{a,A}$	$3.67\pm0.1^{a,A}$
	UV-C 13 min	$12.9\pm0.1^{a,A}$	$1.57\pm0.06^{a,A}$	$3.70\pm0.1^{a,A}$
5	Control	$14.0\pm0.7^{a,B}$	$1.49\pm0.05^{a,A}$	$3.83\pm0.1^{a,B}$
	UV-C 7 min	$13.4\pm0.4^{a,B}$	$1.40\pm0.07^{a,A}$	$3.90\pm0.1^{a,B}$
	UV-C 10 min	$13.9\pm0.7^{a,B}$	$1.46\pm0.10^{a,A}$	$3.87\pm0.1^{a,B}$
	UV-C 13 min	$14.3\pm0.2^{a,B}$	$1.45\pm0.07^{a,A}$	$3.83\pm0.1^{a,B}$
10	Control	$14.0\pm0.6^{a,B}$	$1.20\pm0.09^{a,B}$	$3.77\pm0.1^{a,B}$
	UV-C 7 min	$13.2\pm0.8^{a,B}$	$1.30\pm0.06^{a,B}$	$3.90\pm0.1^{a,B}$
	UV-C 10 min	$13.8\pm0.6^{a,B}$	$1.31\pm0.06^{a,B}$	$3.87\pm0.1^{a,B}$
	UV-C 13 min	$13.7\pm0.3^{a,B}$	$1.26\pm0.09^{a,B}$	$3.87\pm0.1^{a,B}$
15	Control	$14.1\pm0.4^{a,C}$	$1.27\pm0.10^{a,B}$	$4.03\pm0.1^{a,C}$
	UV-C 7 min	$14.0\pm0.5^{a,C}$	$1.36\pm0.09^{a,B}$	$3.93\pm0.1^{a,C}$
	UV-C 10 min	$14.5\pm0.2^{a,C}$	$1.24\pm0.11^{a,B}$	$3.97\pm0.2^{a,C}$
	UV-C 13 min	$15.5\pm0.2^{a,C}$	$1.18\pm0.03^{a,B}$	$4.00\pm0.2^{a,C}$

3.4 Weight loss at refrigeration and room temperature

Weight loss of control and irradiated Cape gooseberries throughout refrigerated storage is shown in **Figure 3**. The findings revealed a progressive weight loss across all evaluated conditions, which were intensified with prolonged storage. The interaction between the treatment and storage time was not significant ($F_{15, 486} = 1.2$; $p = 0.2652$). The comparative analysis of the average weight loss for each treatment on the same day indicated significant differences between the UV-C irradiated and the control samples ($F_{3,486} = 71.19$; $p < 0.0001$). Moreover, significant differences were observed among the irradiated fruit samples. Fruits treated with UV-C light for 10 minutes and 13 minutes exhibited significantly higher weight loss percentages compared to those treated with UV-V for 7 minutes. On the other hand, during storage at 5 ± 1°C, the weight loss percentages of Cape gooseberries treated and untreated increased significantly ($F_{5, 192} = 486$; $p < 0.0001$) with increasing storage time at 5 ± 1°C. After 30 days of storage, weight loss percentages ranged approximately between 10% and 18%, the highest values corresponding to the irradiated fruits.

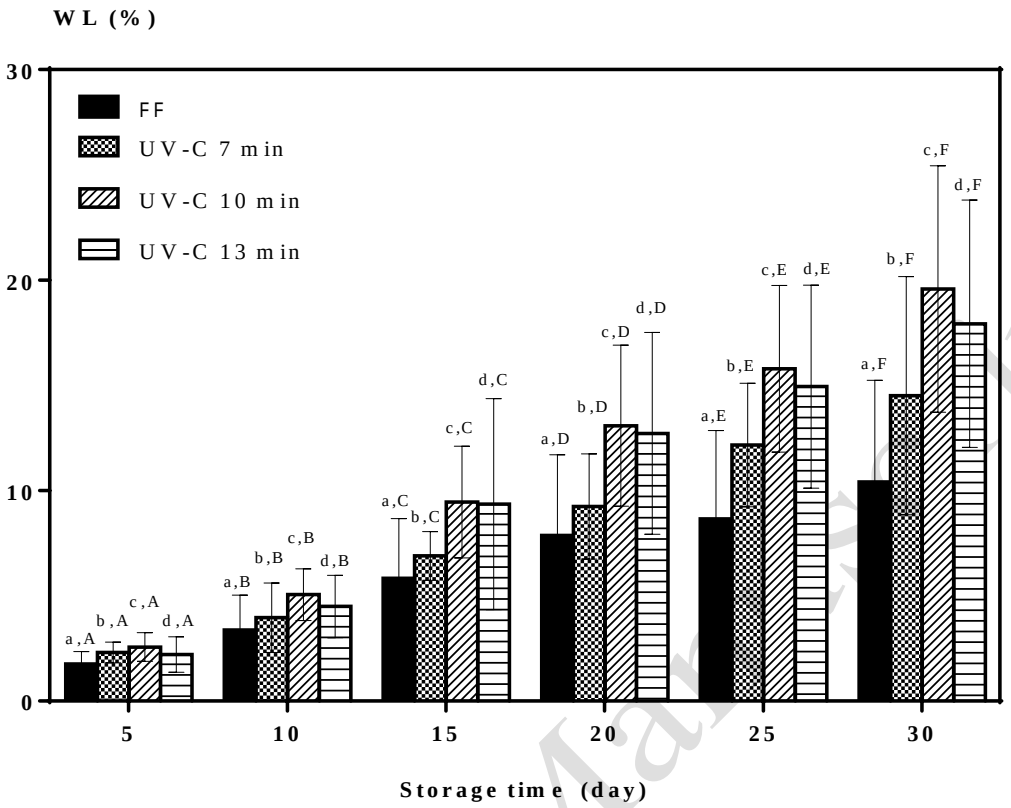

Figure 3. Average WL (%) values of fresh and UV-C treated Cape gooseberries stored at 5 ± 1 ºC for 30 days. Vertical bars represent standard deviations. Bars identified with the same lowercase letter (a) indicate no significant differences ($p < 0.05$) between treatments; bars identified with the same uppercase letter (A) indicate no significant differences ($p < 0.05$) between storage days.

Concerning room temperature, the determination of weight loss percentages was conducted for all evaluated conditions. However, with the treatment of 13 minutes of UV-C irradiation, the percentage of infected fruits increased as the storage days progressed, leading to the discarding of fruits. Consequently, the averages for this condition (13 min) represent less than 50% of the initially evaluated fruits on day zero (final n < initial n). Thus, this data was excluded from the statistical analysis to avoid an imbalance in the number of samples compared to the other treatments. Weight loss of control and irradiated Cape gooseberries throughout refrigerated storage is shown in **Figure 4.**

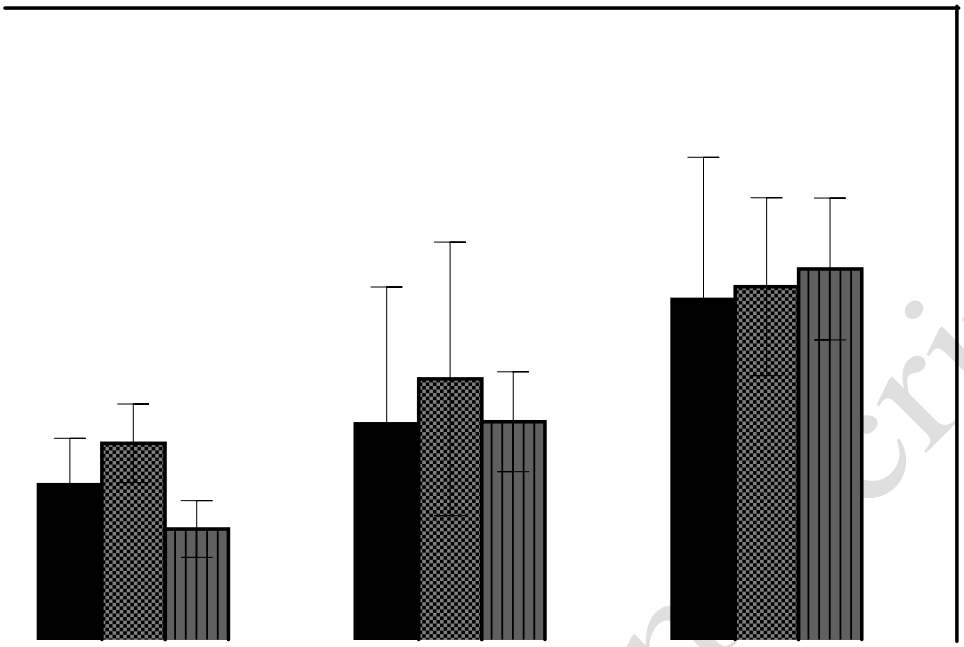

Figure 4. Average WL (%) values of fresh and UV-C treated Cape gooseberries stored at 24 ± 1 ºC for 15 days. Vertical bars represent standard deviations. Bars labelled with the same lowercase letter (a) indicate no significant differences ($p < 0.05$) between treatments, while bars labelled with the same uppercase letter (A) indicate no significant differences ($p < 0.05$) between storage days.

The weight loss percentage was higher than fruits stored under refrigeration. Similar observations were made for fruits stored at refrigeration temperature. The results for this variable also demonstrated weight loss in both control and irradiated samples during storage at room temperature. However, the weight loss percentage (WL, %) of fruits stored at room temperature was higher than that of fruits stored under refrigeration. No significant interaction between the treatment and the storage time was observed ($F_{4, 135} = 1.95$; $p = 0.1052$), but the main effects of each factor were statistically significant. The percentage of weight loss of irradiated and control fruits did not show significant differences ($F_{2, 135} = 2.32$; $p = 0.1020$). However, significant decline in weight ($F_{2, 135} = 77.9$; $p < 0.0001$) was observed during storage at 24 ± 1 °C. For fruits irradiated with UV-C light for 7 and 10 minutes, a slight, albeit not significant, increase in WL (%) compared to the control was observed ($F_{2, 135} = 2.32$; $p = 0.1020$). No significant differences were observed between irradiated samples. The WL (%) of both control and UV-C treated samples significantly increased ($F_{2, 135} = 77.9$; $p < 0.0001$) with the duration of storage at room temperature (24 ± 1 °C). Weight loss measurements recorded in this work could be closely associated with slight modifications in epicuticular waxes and the cuticle provoked by UV-C radiation, as mentioned earlier [11]. A plausible hypothesis for the observed phenomena is that the temperature increase (33 ± 1°C at the end of the treatment) on the surface of the Cape gooseberry fruit, induced by irradiation, may facilitate the more pronounced release or modification of waxes in these fruits, as compared to those in

the control group not subjected to irradiation [27]. A possible explanation could be that the increase in temperature (33 ± 1°C at the end of the treatment) of the Cape gooseberry fruit surface due to irradiation could lead to the easier release or alteration of waxes in these fruits, in larger quantities compared to fruits that were not exposed to irradiation (control) [28]. The removal of waxes resulted in excessive water loss in the fruits and, consequently, an increase in their weight loss. A number of studies mentioned that the percentage of weight loss in berries is strongly related to the integrity of the cuticle and epicuticular waxes on the fruit skin, as these hydrophobic substances act as a barrier to reduce water loss [22, 23 29]. Higher temperatures increase the transfer of mass (water) through the tissue. Therefore, it is logical in this study that the percentage of weight loss was higher in samples stored at room temperature, even though they underwent the same treatments as fruits stored at refrigeration temperature. Weight loss percentage is a critical quality factor, as excessive dehydration of fruits results in visual shrinkage with wrinkled skin, making the fruit unappealing to consumers. Some studies have indicated that water loss equivalent to 5% of the fresh weight of berries can affect the commercial value of these fruits [11]. Thus, it is important to consider that, although there was no microbial growth during the first 20 days of refrigeration storage, weight loss may limit the shelf life of these fruits.

3.5 Effect of UV-C light on total phenol content assessed by the Folin Ciocalteu method.

The total phenol content was reported as mg of gallic acid equivalents per gram of DE (mg GAE/g DE). A two-factor ANOVA was conducted to determine significant differences between the evaluated samples. Statistical analysis indicated no significant interaction ($F_{2, 12} = 3.77$; $p = 0.0536$) between the treatment and the storage time. As observed in **Figure 5**, the total phenolic content in samples treated with UV-C was significantly higher compared to FF ($F_{1,12} = 12.46$, $p = 0.0041$). On the other hand, during storage the total phenolic content did not exhibit significant differences ($F_{1,12} = 2.28$, $p = 0.1449$) and remained practically constant in the control fruits. In contrast, a slight, non-significant increase was observed in the irradiated samples.

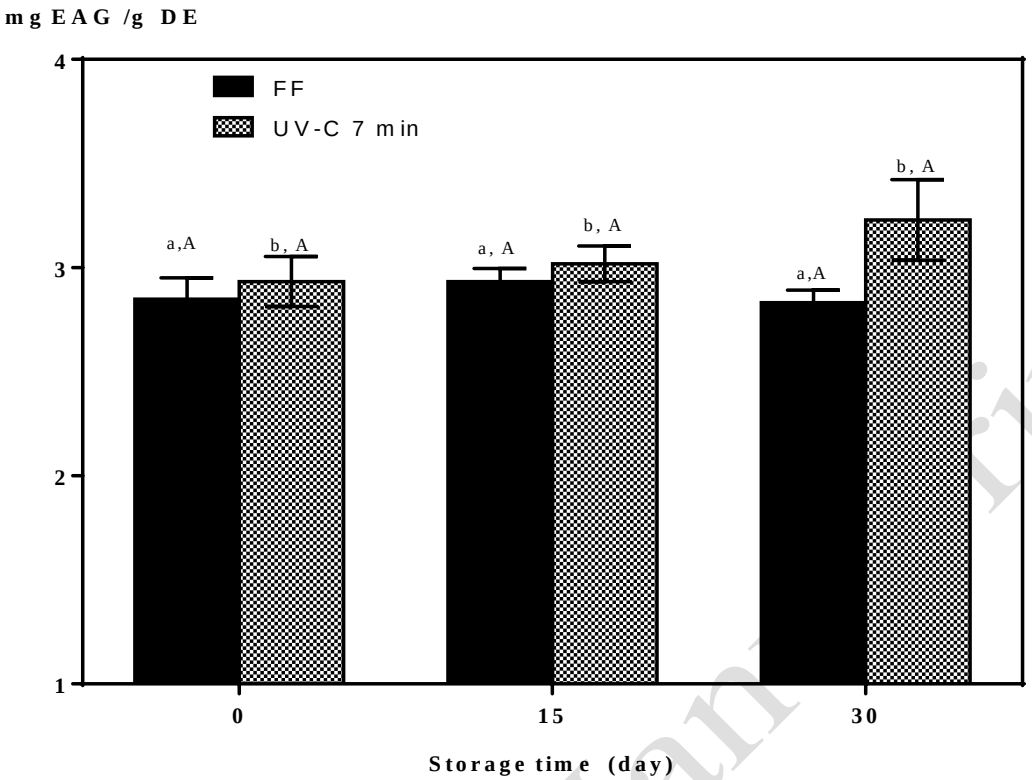

Figure 5. Mean total phenol content per gram of dry extract (mg gallic acid equivalents (GAE)/g DE) in fresh fruits (FF) and fruits irradiated with UV-C light for 7 minutes. Vertical bars represent standard deviations. Bars labelled with the same lowercase letter (a) indicate no significant differences ($p < 0.05$) between treatments, while bars labelled with the same uppercase letter (A) indicate no significant differences ($p < 0.05$) between storage days.

According to the existing knowledge, there is limited literature on the effects of UV-C irradiation on Cape gooseberry. However, numerous studies have shown that plants, fruits, and vegetables activate defence mechanisms in response to biotic stress induced by external factors such as ozone, irradiation, among others [30, 31, 32]. In certain berries, such as grapes, strawberries, and blueberries, the polyphenol profile has been altered or enhanced through UV-C light stimulation, promoting the synthesis of key enzymes like phenylalanine ammonia-lyase (PAL), tyrosine ammonia-lyase (TAL), and p-coumarate ligase, among others [33, 34; 35]. The phenolic compounds in Cape gooseberry represent a significant group of secondary metabolites, widely recognised for their antioxidant, anti-inflammatory, and anticancer properties. Notable among these are phenolic acids such as gallic, chlorogenic, and caffeic acids, as well as flavonoids like quercetin, kaempferol, and myricetin. These compounds play a critical role in protecting the plant against oxidative stress and pathogenic attacks, while also contributing to the nutritional and functional stability of the fruit. Moreover, the phenolics in Cape gooseberry not only confer health benefits through their free radical-scavenging capabilities, but they also directly influence over the sensory qualities and shelf life of the fruits, marking their importance in both the agrifood and therapeutic sectors [1, 36].

3.6 Effect of UV-C light on the antioxidant capacity (AC) of Cape gooseberry assessed by DPPH and FRAP assays

The antioxidant activity in all experiments was developed using techniques (DPPH and FRAP), because antioxidants can act by different mechanisms, depending on the free radical or oxidant used in the test. DPPH method is based on measuring the ability of a sample to capture said free radical. The DPPH solution has an intense violet colour which, when mixed with an antioxidant substance, experiences a discoloration that could reach a light-yellow colour [37]. On the other hand, FRAP (Ferric ion Reducing Antioxidant Power) method measures the reduction capacity of a colourless complex formed by TPTZ (2, 4, 6-tripyridyl-s-triazine) and ferric iron (Fe^{3+}), to a ferrous complex (Fe^{2+}), which shows an intense greenish-blue colour in the presence of an acidic medium and antioxidant metabolites [38]. The AC values obtained using both methods are shown in **Table 3**, expressed in mg TEAC/g of wet mass (mM TEAC/g). A two-factor ANOVA analysis showed a significant interaction between the treatment and storage time factors in both DPPH and FRAP methods ($F_{2, 12} = 9.69$; $p = 0.0031$; $F_{2, 12} = 12.81$; $p = 0.0011$, respectively). Results were expressed as mean ($n = 3$) ± standard deviation of the sample. Mean values within the same column identified with the same uppercase letter showed no significant differences ($p < 0.05$) between treatment and storage days.

Table 3. Mean values and corresponding standard deviations of antioxidant capacity of fresh (control) and treated Cape gooseberries (7 min of UV-C light exposure) and stored at 5 ± 1°C for 0, 15, and 30 days

Day	Treatment	DPPH (mg TEAC/g)	FRAP (mg TEAC/g)
0	FF	1.08 ± 0.07^{A}	2.61 ± 0.09^{A}
	UV-C 7 min	$1.23\pm0.08^{A,D}$	3.51 ± 0.12^{B}
15	FF	1.59 ± 0.03^{B}	3.19 ± 0.15^{C}
	UV-C 7 min	$1.51\pm0.05^{B,C}$	3.59 ± 0.09^{B}
30	FF	$1.37\pm0.05^{C,D}$	$3.43\pm0.11^{B,C}$
	UV-C 7 min	1.27 ± 0.01^{D}	3.69 ± 0.13^{B}

According to the DPPH-based AC values, a slight significant increase in AC values of irradiated samples compared to control samples was observed for days 0 and 15 of storage. During storage, AC values showed a slightly significant increase on day 15. Nonetheless, for day 30 this value was significantly decreased compared to day 0. The FRAP-based AC values showed a significant increase in irradiated samples compared to the control. However, during storage, these values did not change significantly. In general, the antioxidant capacity (AC) of fruits is primarily attributed to hydrophilic antioxidants, such as ascorbic acid, anthocyanins, and phenolic compounds, as well as lipophilic antioxidants, including carotenoids. The observed increase in AC may be linked to the rise in phenolic content in Cape gooseberry, which, in turn, could be associated with various protective mechanisms that plants, fruits, and vegetables activate in response to biological stress caused by external factors, such as irradiation [31]. The literature offers numerous studies evaluating the impact of UV radiation on both whole and freshly cut fruits and vegetables, particularly focusing on the modulation of bioactive compounds. The specific compounds induced by UV exposure are largely contingent on the species, cultivar, and other influencing factors. Notable increases in phenolic acids, non-anthocyanin flavonoids, anthocyanins, other

flavonoids, isoflavones, and stilbenes have been widely documented. Additionally, enhanced antioxidant capacity in response to UV (A, B, C) light has been observed in various fruits, including blueberries, tomatoes, apples, strawberries, cherry tomatoes, and grapes [15, 32]. Howbeit, the literature does not present a universal consensus on this matter, as some studies have reported that UV light irradiation did not lead to an increase in bioactive compounds across different fruit matrices.

3.7 Correlation between phenolic compounds/DPPH/FRAP

The results partially align with those previously reported [25]. These authors noted that UV-C light treatment significantly increased the antioxidant capacity and total phenol content of Cape gooseberry, possibly due to the activation of the phenolic compound biosynthesis pathway in response to UV radiation. Literature highlights numerous relevant publications assessing the effect of UV radiation on whole and freshly cut fruits and vegetables, focusing on bioactive compounds. The induced compounds largely depend on the species considered, cultivar, among other factors. Increases in phenolic acids, non-anthocyanin flavonoids, anthocyanins, other flavonoids, isoflavones, and stilbenes have often been reported [33, 35]. The increase in antioxidant capacity in response to UV (A, B, C) light has been evaluated in various fruits, including blueberries, tomatoes, apples, strawberries, cherry tomatoes, grapes, among others [15, 32]. However, there is no universal agreement in the literature on this topic; several studies have also reported that UV light radiation did not increase bioactive compounds in different fruit matrices.

4. Conclusions

The short-wave ultraviolet (UV-C) radiation treatments, applied at the studied exposure times and during the proposed storage periods at 5 ± 1°C and 24 ± 1°C, produced varying effects on the native microbiota of Cape gooseberry fruits, influenced by both exposure duration and storage temperature. The treatment that, on average, showed the best results in fungal inhibition percentage was UV-C light for 7 min. The 7-minute UV-C light treatment significantly delayed fungal development in Cape gooseberry fruits stored at 5 ± 1°C and 24 ± 1°C compared to the control. Likewise, a significant difference was observed in the onset of fungal contamination in fruits irradiated for 7 minutes and stored at 5 ± 1°C, compared to fruits irradiated for 7 minutes and stored at 24 ± 1°C; fungal contamination started on days 22 and 11, respectively. The 10 and 13-minute UV-C light treatments did not present an inhibitory effect on the fungal development of Cape gooseberry fruits stored at 5 ± 1°C and 24 ± 1°C; the percentage of infected fruits for these two treatments was significantly higher than that of control fruits. The results obtained for these exposure times were associated with possible modifications caused by UV-C radiation on the epicuticular waxes and cuticle of these fruits. The percentage of infected fruits increased during storage in all evaluated conditions. In general, the UV-C light treatments did not affect the soluble solids content, pH, and titratable acidity of Cape gooseberry fruits, compared to control fruits, for both evaluated temperatures. During storage at 5 ± 1°C and 24 ± 1°C, there was a general increase in the values of soluble solids and pH, and a decrease in titratable acidity for all evaluated treatments, associated with processes inherent to the ripening of these fruits, rather than treatment effects. The weight loss percentage of Cape gooseberry fruits irradiated with UV-C light and stored at 5 ± 1°C was significantly higher than that of the control. Fruits exposed to 10 and 13 minutes of irradiation resulted in higher WL (%) than fruits irradiated for 7 minutes. The weight loss percentage of Cape gooseberry fruits irradiated with UV-

C light for 7 and 10 minutes and stored at 24 ± 1°C did not show significant differences compared to the control; however, the WL (%) of irradiated fruits was slightly higher. WL (%) increased during storage at both evaluated temperatures, potentially limiting the shelf life of these products. There was a significant increase in the phenols content and antioxidant capacity of Cape gooseberry fruits irradiated for 7 minutes and stored at 5 ± 1°C, during 0 and 15 days. During storage, these values did not change significantly. According to the results obtained, UV-C light treatment could be used as an alternative conservation strategy to extend the shelf life of Cape gooseberry fruits without significantly affecting their physicochemical parameters. However, it is important to consider the exposure times to UV-C light as they could affect the epicuticular waxes and/or the cuticle, thus promoting weight loss of Cape gooseberry fruits and fungal attack on them.

Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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Author contributions

Analyzed data: G. M. Jaramillo-Sánchez and J. K. Bueno-Cuenca:. G. M. Jaramillo-Sánchez, N. L. Matute-Castro, S. E. Córdova-Márquez, and A. C. Solano-Solano; conducted experiments and developed methodology: G. M. Jaramillo-Sánchez, J. K. Bueno-Cuenca, N. L. Matute-Castro, M. Campo-Fernández, and V. P. Bravo-Bravo; managed research planning: G. M. Jaramillo-Sánchez, J. K. Bueno-Cuenca, N. L. Matute-Castro, M. Campo-Fernández, and V. P. Bravo- Bravo; provided resources: N. L. Matute-Castro, M. Campo-Fernández, and V. P. Bravo-Bravo; led planning and execution: G. M. Jaramillo-Sánchez and J. K. Bueno-Cuenca; ensured reproducibility: G. M. Jaramillo-Sánchez, A. C. Solano-Solano and N. L. Matute-Castro; drafted and prepared the manuscript: G. M. Jaramillo-Sánchez, M. Campo-Fernández and S. E. Córdova-Márquez:

Data availability statement

Data supporting the findings, including microbial growth assessments, quality parameters, and antioxidant capacity measurements, can be made available from the corresponding author upon

reasonable request. Requests for data will be considered in accordance with institutional policies and the consent of all contributing researchers.

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