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Research article

Postharvest of fresh white shimeji mushroom subjected to UV-C radiation

Milanna Paula Cabral Nunes [a], Igor Leonardo Vespucci [b], Pedro Augusto Resende Rimoli [c], Cristiane Maria Ascari Morgado [a,*], André José de Campos [a]

[a] Universidade Estadual de Goiás (UEG), Campus Central, Rodovia BR 153, km 99, Anápolis, GO CEP 75132-903, Brazil
[b] Universidade Federal de Goiás (UFG), Escola de Agronomia (EA), Campus Samambaia, Rodovia Goiânia-Nova Veneza, Km 0, s/n, Goiânia, GO CEP 74690-900, Brazil
[c] Universidade Estadual do Oeste do Paraná (UNIOESTE), Rua Pernambuco, 1777, Centro, Marechal Cândido Rondon, PR CEP 85960-000, Brazil

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ABSTRACT

This study aimed to evaluate the postharvest characteristics of edible fresh white shimeji mushrooms under different UV-C radiation doses. The experimental design used was fully randomized, in a 5 × 8 factorial scheme (UV–C radiation dose: 0 (control), 1, 2, 3, and 4 kJ m^{-2} x day of analysis), with 3 replications of 70 ± 1 g mushrooms each. After exposure to different doses, they were stored at 2 ± 0.5 °C and 60 ± 3.8 % RH. Data were subjected to permutational multivariate analysis (PERMANOVA) ($p \leq 0.05$). There was no significance for interaction, nor the factor day, only for the UV-C radiation doses factor. Regarding PCA, among the doses applied, the dose of 2 kJ m^{-2} was effective in maintaining the quality of mushrooms with greater lightness, greater whiteness index, a greater amount of total extractable polyphenols, and total antioxidant activity. In conclusion, the dose of 2 kJ m^{-2} was effective in maintaining the postharvest quality of white shimeji mushrooms.

1. Introduction

Edible mushrooms have grown in popularity as a functional food, resulting in increased demand and consumption in recent decades around the world. The growing demand is due to its nutritional properties, namely: amounts of proteins, fibers, vitamins, minerals, carbohydrates, and essential amino acids, in addition to medicinal properties, such as prevention of cardiovascular and degenerative diseases, improvement in the immune system and antitumor and antioxidant functions. Several compounds in mushrooms are responsible for these benefits, especially the bioactive components [1–4].

The consumption of shimeji mushrooms worldwide primarily in the form of fresh mushrooms, makes it occupy the second position among the cultivated species of edible mushrooms [5] and represents 24 % of Brazilian production [6]. However, mushrooms tend to lose quality quickly after harvesting and may degrade in 1–3 days at room temperature, around 22 °C [7,8]. Therefore, extending the post-harvest shelf life is a constant search in the mushroom production and supply chain [8]. In this way, there is a need to adapt techniques to maintain the quality of these mushrooms, increasing their shelf life and reducing nutritional losses [9].

* Corresponding author.
E-mail address: cristiane.morgado@ueg.br (C.M.A. Morgado).

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Among the post-harvest techniques, cooling is the most widely used to prolong the shelf life of edible mushrooms. However, it has a limited effect on mushroom browning. Therefore, other methods have been used, such as packaging, edible coatings, chemical treatments, ozone treatments, ionizing and non-ionizing irradiation, among others. All these treatments are focused on prolonging the shelf life of mushrooms [10]. Nonetheless, these techniques have imperfections such as water accumulation on the surface, application complexity, requirements for maintaining humidity and temperature, in addition to high expenses with equipment and reagents, thus, improvements and associated uses of techniques [4].

Studies to improve these techniques have advanced and shown positive effects by using radiation to control browning in mushrooms: UV-C [11–13], gamma radiation [14–16], and electron beam radiation [17]. In this context, non-ionizing radiation arises as a technique that acts to maintain the quality and safety of food, in addition to prolonging shelf life, as it eliminates foodborne diseases [18,19].

Thus, radiation, especially UV-C, can suppress enzymatic browning due to its antibacterial properties, increasing total antioxidant capacity and reducing polyphenol-oxidase (PPO) activity [13,16]. UV-C is a non-toxic and non-invasive method with several advantages, which include the absence of chemical residues, zero waste generation, cost-effectiveness (low installation and maintenance costs), ease of implementation, environmental friendliness, low energy consumption, minimal impact on nutritional quality and organoleptic characteristics, and favorable consumer perception [20–22].

It is important that the dosage and exposure time should be checked to avoid tissue damage and counteract anti-browning activity [11]. Thus, the use of UV-C radiation has been studied by different authors with the aim of extending the shelf life of mushrooms as well as maintaining their quality. Wang et al. [4] applied UV-C radiation at a dose of 4.0 kJ m^{-2} and subsequently packaged the mushrooms in low-density polyethylene bags and stored them at 4 °C for 15 days. They concluded that the mushrooms exhibited slower changes in color, as well as in the content of soluble solids, and overall had better quality compared to untreated mushrooms.

The effect of UV-C radiation on mushrooms was investigated by Wu et al. [23], who exposed *Agaricus bisporus* mushrooms to a radiation dose of 1.0 kJ m^{-2} and stored them for 21 days at 4 °C. The authors concluded that the dose was effective in increasing the antioxidant capacity of the mushrooms.

Based on the above, our study aimed to evaluate the postharvest characteristics of fresh white shimeji mushrooms subjected to different UV-C radiation doses, in order to determine the optimal UV-C radiation dose that would preserve their quality during postharvest storage.

2. Material and methods

2.1. Origin and preparation of mushrooms

In this section, the origin and preparation of mushrooms were described.

White shimeji mushrooms were harvested in April 2020, in the commercial cultivation shimeji Shop, located at 16°41′39.8″ S latitude and 49°17′02.6″ W longitude, in the city of Goiânia-GO, Brazil.

Basidiocarps were harvested manually and, after harvesting, they were transported in an acclimatized environment, using vehicular air conditioning (19 °C), in expanded polystyrene (EPS) boxes, to the Post-harvest laboratory of the Research Center and Graduate Studies (CPPG), from the Central Campus, Anápolis (CET), from the State University of Goiás, Anápolis/GO, Brazil.

In the laboratory, mushrooms were manually and visually selected for lot uniformity in terms of color, size, and shape, according to commercialization standards [24], that is, white in color, without viscous sensation, free from stains, and mechanical trauma. Later, all manually adhered soil was removed through delicate movements. All procedures were carried out with the assistance of disposable nitrile gloves to handle the mushrooms in order to reduce direct contact with hands and avoid causing any damage to them.

2.2. Experimental procedure

In this section, the execution of the experiment was described, detailing the steps and procedures that were followed.

The mushrooms were exposed to different UV-C radiation doses, during different exposure times, and then stored in a passive modified atmosphere. They were packed in polyvinyl chloride (PVC) + expanded polystyrene (EPS) packaging. The design used was fully randomized (DIC), in a 5 × 8 double factorial scheme (UV–C radiation dose x day of analysis), with 3 repetitions, and each repetition composed of 70 ± 1 g mushrooms per package, totaling 8.4 kg basidiocarps.

Five UV-C irradiation doses were used: 0 (control), 1, 2, 3, and 4 kJ m^{-2}, in which the mushrooms remained in the prototype for 0.0, 67.41, 134.83, 202.24, and 269.66 s, respectively. A photoradiometer (Delta OHM, HD2302.0, Caselle, Italy) was used to verify the radiation emitted by the prototype, expressed W m^{-2}. After that, the exposure times to the UV-C source were determined, thus, the doses were expressed in kJ m^{-2}.

The prototype of UV irradiation used had a cylindrical plastic polymer chamber and two unfiltered 30-W germicidal lamps, one at the top and one at the bottom, connected in parallel, with a geometric structure of 0.5 × 0.5 × 0.9 m (width × height × length) and galvanized drawn wire, dividing the equipment into upper and lower parts. The lamps had a wave amplitude of 254 ηm.

Mushrooms were stored in a BOD type (Biochemical Oxygen Demand) chamber, at 2 ± 0.5 °C and 60 ± 3.8 % RH, for 14 days, and were evaluated every 2 days (0, 2, 4, 6, 8, 10, 12, and 14 days).

2.3. Analyzed variables

In this section, we outlined the variables that were analyzed during the experiment.

2.3.1. Weight loss

The weight loss (WL) was determined using a digital precision scale (Shimadzu, BL 3200H, Kyoto, Japan) with a 0.5-g precision and 3200-g maximum load, considering mushroom initial weight, as results expressed as percentage.

2.3.2. Firmness

The firmness (F) was measured by a texturometer (Brookfield - *Texture Analyser* CT3 50K, Middleborough, USA) by compression at 5.0 mm s^{-1} speed and 15 mm deformation, TA-11 cylindrical probe tip, 3.8 cm in diameter and 1.9 cm in height, two readings on the cap and two on the stipe, with results expressed as Newton (N).

2.3.3. Soluble solids

The soluble solids (SS) were determined by refractometric reading (in %) at 20 °C using a portable digital refractometer (Reichert Brix, RI-Check, Buffalo, USA), according to the method of AOAC [25].

2.3.4. pH

The hydrogen potential (pH) was determined by a digital pH meter (Tecnal, R-Tecnal-7-MP, Piracicaba, Brazil), following the AOAC [25].

2.3.5. Coloration

The coloration (C) was determined by reflectance in a portable colorimeter CR-400 (Konica Minolta, Osaka, Japan), in which L* indicates lightness [dark (L* = 0) and light (L* = 100)], a* indicates redness-greenness [red (a* = 100) and green (a* = −100)] and b* indicates yellowness-blueness [yellow (b* = 100) and blue (b* = −100)]; from a* and b*, the following were calculated: Chroma (color saturation), °Hue (color saturation) [26]. Browning Index (BI) and Whiteness Index (WI) according to Borchert et al. [27], and color difference (CD) [28].

2.3.6. Bioactive analyses

In this section, the determination of bioactive compounds was addressed. Samples were frozen for later bioactive analyses. For total antioxidant activity and total extractable polyphenols, samples were dried in circulation and air renewal oven (Tecnal, TE-394/2-MP,

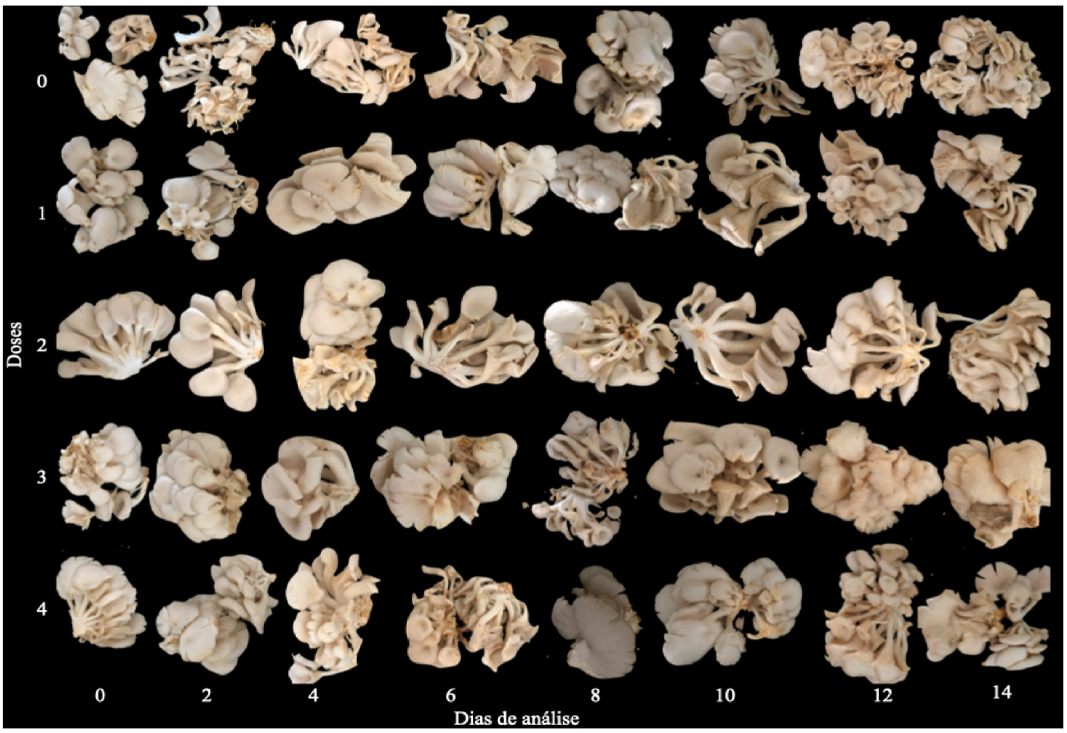

Fig. 1. Postharvest conservation of fresh white shimeji mushroom subjected to different UV-C radiation doses (0, 1, 2, 3, and 4 kJ m^{-2}) and stored at 2 ± 0.5 °C and 60 ± 3.8 %UR, for 14 days in a BOD chamber.

Piracicaba, Brazil) at 65 °C for 4 h [29], and stored in a silica desiccator, in dark packaging, until the time of analysis.

2.3.6.1. Total antioxidant activity by DPPH method. Total antioxidant activity was determined using free radical scavenging methods for DPPH (2,2-diphenyl-1-picrylhydrazyl), with results expressed as EC50 g dried mushroom g^{-1} DPPH. Absorbance was measured in a spectrophotometer (Instrutherm, UV-2000A Visible, São Paulo, Brazil) at 515 ηm for DPPH 6 min after sample addition [30].

2.3.6.2. Total antioxidant activity by ABTS method. Total antioxidant activity was determined by ABTS [2,2′-AZINO-BIS (3-ethyl-benzene-thiazoline-6-sulfonic acid) diammonium salt] [30], with results expressed as μmol Trolox g^{-1} dried mushroom. Absorbance was measured in a spectrophotometer (Instrutherm, UV-2000A Visible, São Paulo, Brazil) at 734 ηm for ABTS, minutes after sample addition.

2.3.6.3. Total extractable polyphenols (TEP). The levels of total extractable polyphenols were quantified using the Folin Ciocalteu method as per Rufino et al. [30]. The results were expressed in mg of gallic acid per 100 g of dried mushrooms.

2.4. Statistical analysis

In this section, the statistical analysis conducted for the experiment was addressed.

The results were subjected to permutational multivariate analysis (PERMANOVA) ($p \leq 0.05$). When significant, principal component analysis (PCA) was performed using a Euclidean distance matrix, through R software v. 4.0.3 [31].

Three criteria were used to select principal components. The first, suggested by Jolliffe et al. [32], states that components with eigenvalues below 0.7 are liable to be discarded [33]. Another criterion was to consider eigenvalues equal to or above 1.0, since original variables also have variance equal to 1.0 after standardization [34,35]. The third criterion was proposed by Rencher [36], in which at least 70 % of the total variance must be explained by the first two principal components.

3. Results and discussion

Fig. 1 shows the postharvest conservation of fresh white shimeji mushrooms subjected to different UV-C radiation doses and stored at 2 ± 0.5 °C for 14 days. The dose of 2 kJ m^{-2} was efficient in color conservation since preserved fruits were suitable for consumption for more days (Fig. 1). Mushroom whiteness index on the 14th day was 19.20, 20.58, 21.13, 11.03, and 20.67 for 0, 1, 2, 3, and 4 kJ m^{-2}, respectively. Therefore, the dose of 2 kJ m^{-2} maintained whiteness levels higher until the end of storage (Fig. 1).

Such behavior can be explained by an effect known as hormesis. Hormesis is the most potent intrinsic protective mechanism against life-threatening ischemic and oxidative challenges in multiple organ systems [37]. It represents a dose-response phenomenon characterized by low-dose stimulation and high-dose inhibition, which can be graphically depicted as either an inverted U-shaped dose-response curve or a J- or U-shaped dose-response curve [38]. A similar result has already been observed in edible mushrooms *Agaricus bisporus* after the application of low fungicide doses [39].

Regarding the dose of 2 kJ m^{-2}, similar results were found by Wang et al. [4], who reported better color preservation in *Pleurotus ostreatus* after 15 days of cold storage at 4 °C, with the application of 2 kJ m^{-2} UV-C. Lu et al. [12,40] also reported that UV-C treatment can reduce the browning of button mushrooms.

According to PERMANOVA ($p \leq 0.05$), neither interaction nor the factor days were significant, only the factor UV-C radiation doses. Therefore, the principal component analysis (PCA) was developed using only the factor doses.

Table 1 presents the eigenvalues, explained variance percentage, and accumulated explained variance. Only four principal components were identified (PC1, PC2, PC3, and PC4), as the others were discarded for having eigenvalues below 0.7 and accumulated variance reached 100 % in PC4. PC1 and PC2 explained more than 70 % of the data variability, with PC1 accounting for 47.10 % and PC2 for 26.22 %, with eigenvalues above 1.0, i.e., representative. PC3 totalled 94.23 % of the accumulated explained variance, but only 20.91 % of the variance explained by the components. Therefore, PC1 and PC2 were selected for the PCA, because they explain with greater variance the behavior in our study.

Pearson's correlation coefficients for the evaluated characteristics ranged from −0.864 to 0.965 (Table 2). When analyzing eigenvectors, the parameters lightness (L*), whiteness index (WI), pH, soluble solids, total antioxidant activity by the ABTS method, and total extractable polyphenols (TEP) had the highest positive correlation. On the other hand, total antioxidant activity by the DPPH method had the highest negative correlation for PC1. Therefore, as positive parameters increase, the opposite occurs with antioxidant

Table 1
Principal components (PCs), eigenvalues, percentage of variance explained by components (PCv) and percentage of accumulated explained variance (PCav) of the characteristics evaluated fresh white shimeji mushrooms subjected to different UV-C radiation doses.

Principal Component	Eigenvalue	PCv (%)	PCav (%)
PC1	6.1231	47.10	47.10
PC2	3.4082	26.22	73.32
PC3	2.7185	20.91	94.23
PC4	0.7501	5.77	100.00

Table 2
Correlation eigenvectors between variables in the first three principal components (PC1, PC2, and PC3) of physical, physicochemical, and bioactive characteristics of fresh white shimeji mushrooms subjected to different UV-C radiation doses.

Eigenvector	PC1	PC2	PC3
Weight loss (WL)	−0.556	**−0.824**	0.106
Lightness (L)	**0.991**[a]	−0.127	0.028
Browning index (BI)	−0.567	**0.700**	−0.428
Whiteness index (WI)	**0.771**	−0.446	0.427
Color difference (CD)	−0.403	**0.678**	0.439
Chroma (C)	−0.156	**0.825**	−0.533
°Hue (H)	0.087	**−0.605**	−0.517
Firmness (F)	−0.305	0.385	**0.869**
pH	**0.782**	0.430	0.445
Soluble solids (SS)	**0.769**	0.258	−0.572
Total antioxidant activity (ABTS)	**0.965**	0.156	0.106
Total extractable polyphenols (TEP)	**0.864**	0.253	0.294
Total antioxidant activity (DPPH)	**−0.864**	−0.107	0.461

[a] Numbers in bold highlight variables with the highest correlation observed in each principal component.

activity (DPPH), which is negatively correlated. This is desirable since DPPH radical capture value has to be lower to achieve the greater antioxidant activity, as a smaller amount of sample is needed to reduce the initial amount of DPPH radical by 50 % [41].

As for PC2, the most significant parameters positively correlated were chroma (C), browning index (BI), and color difference (CD), while mass loss (WL) and °Hue (H) were negatively correlated. Such parameters are related to mushrooms with inferior quality, so they would not be easily marketable. Therefore, weight loss and accentuated browning, from losses of water and enzymatic activity, are the main problems to be faced in the post-harvest of mushrooms [42,43].

For PC3, only firmness (F) had a high correlation and eigenvalue above 1.0. Therefore, it was analyzed together with PC1 and PC2 to understand firmness behavior. However, it was not selected to be used in PCA since, for different authors, components are selected due to their importance, that is, greater variance. Therefore, the first component that represents the maximum data variability was chosen, followed by the second with the highest value [44–46]. The third component represents about 20 % of the data variability, a lower value than the first and second components.

The PCA completely distinguished the doses, and thus were significantly different from each other. The PCA result showed that the dose 4 kJ m^{-2} was more distant from the others, therefore it had distinct characteristics as it was not grouped close to the most representative vectors. On the other hand, the doses 0 (control) and 3 kJ m^{-2} were shown to be close, probably because they had

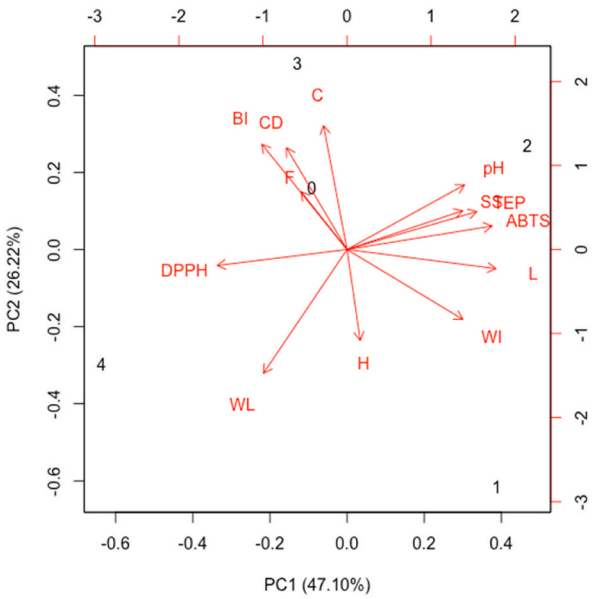

Fig. 2. Principal component analysis for physical, physicochemical, and bioactive quality parameters of fresh white shimeji mushrooms under different UV-C radiation doses. Legend: (0 - control; 1–1 kJ m^{-2} UV-C radiation; 2 kJ m^{-2} UV-C radiation; 3 - 3 kJ m^{-2} UV-C radiation; and 4–4 kJ m^{-2} UV-C radiation). WL: weight loss; L: lightness; BI: browning index; WI: whiteness index; CD: color difference; C: chroma; H: °Hue; F: firmness; pH: hydrogen potential; SS: soluble solids; ABTS: total antioxidant activity by ABTS method; TEP: total extractable polyphenols; DPPH: total antioxidant activity by DPPH method. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

similar results, showing mushrooms with browning characteristics. Meanwhile, the doses 1 and 2 kJ m^{-2} remained isolated, one in each quadrant, with the dose 1 kJ m^{-2} having no evident positioning of vectors and the dose 2 kJ m^{-2} being correlated with desirable vectors for post-harvest of edible mushrooms (Fig. 2).

When analyzing parameters with the highest positive correlation in the PC1, L*, WI, pH, SS, ABTS, and TEP showed proximity to the dose of 2 kJ m^{-2}. Such vectors represent desirable characteristics for the post-harvest quality of mushrooms, showing higher antioxidant activity, whiteness, lightness, and pH.

The dose of 2 kJ m^{-2} increased in pH, which may have inhibited microbial growth. Han Lyn et al. [9] observed that the proliferation of microorganisms, such as *Clostridium botulinum*, or anaerobic respiration in mushrooms, leads to a reduction in pH. By evaluating electrolyzed water in mushrooms, Ding et al. [47] concluded that microbial growth inhibition reduced the production of organic acids, therefore, little variation in pH. Reduction of the microbial load is desired after UV-C application, which aims to reduce the number of microorganisms, control the onset of diseases, and hence product deterioration [48–51].

Both WI and L* were closer to the dose of 2 kJ m^{-2}, which is favorable to the postharvest quality of mushrooms. Therefore, the dose 2 kJ m^{-2} was efficient in maintaining brightness, represented by L*, and preserving white color throughout white shimeji mushrooms storage. As for Ojeda et al. [52], browning substantially reduces the acceptance of mushrooms by consumers, a fact of great importance in this study.

During the natural senescence of mushrooms, carbohydrates are hydrolyzed into sugars, which increases SS contents [53]. The dose of 2 kJ m^{-2} was efficient in retaining SS, which, for Wang et al. [4], is provided by UV-C radiation. Therefore, this technique can retain SS content in mushrooms and hence preserve high metabolic rates.

The dose 2 kJ m^{-2} is characterized by a greater amount of TEP since it was close to its vector. Moreover, this dose had greater total antioxidant activity because it was located near the ABTS vector, opposite the DPPH [41,54] UV-C irradiated mushrooms have expressed improvements in antioxidant properties by antibacterial properties, a decrease in polyphenol-oxidase (PPO) activity by increasing total phenols and, consequently, less melanin formation [13,16,55–57].

DPPH total antioxidant activity had a negative correlation with PC1, closer to dose 4 and opposite to dose 2. In other words, dose 4 showed a greater amount of DPPH, therefore, lower antioxidant activity. Dose 2 had lower DPPH values, hence higher antioxidant activity. DPPH radical inhibition percentage is expressed as median effective concentration (EC50), which is the amount needed to reduce the initial DPPH radical concentration by 50 % [53]. Thus, according to Oliveira et al. [41], to indicate greater antioxidant activity, DPPH radical scavenging value has to be lower, as it indicates that a smaller amount of sample is needed to reduce the initial DPPH radical content by 50 %, which was verified in our study.

WL and H were negatively correlated with PC2. WL was aligned to dose 4, which also showed proximity to DPPH. Therefore, the highest dose provided higher WL and lower antioxidant activity. According to Barkai-Golan and Follet [19], one of the main problems during postharvest storage of mushrooms is fast dehydration by loss of water, and hence weight loss. This is because mushrooms are coated with a thin epidermal structure, in addition to having high rates of respiration and transpiration [46,58]. Therefore, dose 4 was not effective to maintain WL of white shimeji mushrooms.

In turn, BI, CD, and C were positively correlated with PC2 and aligned and close to doses 0 and 3. Therefore, these doses provided undesirable attributes for the post-harvest of white shimeji mushrooms; therefore, mushrooms were darker and had a greater difference in color and chroma.

Furthermore, chroma (C) is directly related to browning index (BI) of mushrooms since, according to Refs. [59,60], an increase in chroma (C) (color saturation) is an indication for measuring browning index (BI), as increasing chroma (C) values denote an increase in browning and hence darker mushrooms. Changes in color parameters during the storage of several agricultural products, including mushrooms, occur mostly as a result of enzymatic changes, leading to the darkening of products, thus impairing their marketing [61,62].

Lastly, vectors were not positioned for dose 1. Therefore, we could not identify its behavior in the post-harvest of fresh white shimeji mushrooms.

4. Conclusions

Among the doses evaluated and under the conditions in which this study was performed, the dose 2 kJ m^{-2} has satisfactory results in terms of lightness, whiteness index, pH, total extractable polyphenols, and antioxidant activity both by ABTS and DPPH methods.

UV-C radiation is a valuable tool in the mushroom production and manufacturing industry for its ability to enhance food safety, extend shelf life, preserve quality, and reduce the need for chemical preservatives. It aligns with consumer preferences for natural and sustainable food products while also offering economic benefits to producers.

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Data availability statement

Data included in article/supp. material/referenced in article.

CRediT authorship contribution statement

Milanna Paula Cabral Nunes: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Igor Leonardo Vespucci:** Investigation, Formal analysis, Data curation. **Pedro Augusto Resende Rimoli:** Formal analysis, Data curation. **Cristiane Maria Ascari Morgado:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **André José de Campos:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

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

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