Dose-Dependent Effects of LED UV-C on Shelf Life and Quality of Shiitake Mushrooms

Shaanxi University of Technology

yu feng
Shaanxi University of Technology

lina chen
Shaanxi University of Technology

fanshu kong
Shaanxi University of Technology

xu yang
Shaanxi University of Technology

lina meng
Shaanxi University of Technology

chingyuan hu
Qinba State Key Laboratory of Biological Resources and Ecological Environment

chen xu
Shaanxi University of Technology

daihua hu
Hudaihua@snut.edu.cn

Shaanxi University of Technology

Case Report

Keywords: LED UV-C, Postharvest preservation, Shiitake mushrooms, Nutritional quality, Nonthermal processing

Posted Date: December 22nd, 2025

DOI: https://doi.org/10.21203/rs.3.rs-8379521/v1

Additional Declarations: No competing interests reported.

Abstract

Shiitake mushrooms (Lentinula edodes) are valued for their nutritional and bioactive compounds but suffer rapid quality deterioration postharvest due to high moisture and microbial activity. This study applied LED-generated UV-C irradiation at doses of 0.67, 1.33, and 2.66 kJ/m² to fresh shiitake mushrooms stored at 4°C for 21 days, assessing color, weight loss, proteins, bioactive compounds, enzyme activities, microbial load, and sensory attributes. Here we demonstrate that the 2.66 kJ/m² UV-C dose most effectively inhibited microbial growth, reduced weight loss, and preserved total phenolic content, while lower doses better maintained soluble proteins and antioxidant enzyme activities. Sensory qualities remained unaffected by UV-C treatment. These findings suggest that LED UV-C irradiation, particularly at 2.66 kJ/m², is a promising non-thermal, eco-friendly technology to extend shelf life and maintain the nutritional quality of shiitake mushrooms during storage.

1. Introduction

Shiitake mushrooms (*Lentinula edodes*), commonly known as Flowering Mushrooms, represent a nutrient-dense fungal species prized for their rich composition of bioactive compounds [1, 2]. These edible macrofungi contain substantial amounts of polysaccharides, proteins, vitamins, dietary fiber, aromatic volatiles, and phytosterols [3, 4]. They also contain approximately 18 amino acids, with glutamic acid being the most dominant. Shiitake mushrooms are one of the richest sources of vitamin D_2 precursors in humans [5]. Their bioactive compounds exhibit clinically significant anticancer and antimicrobial properties, while also demonstrating hepatoprotective effects against cirrhosis and cholesterol-lowering capabilities [6]. Global mushroom production reached 42.8 million metric tons, valued at US$45.2 billion, in 2020, with China accounting for 93% of the total output [7]. Shiitake mushrooms account for 22% of the worldwide edible fungi production, representing 80% of the mushroom industry's total yield in China [8]. This combination of nutritional superiority and large-scale cultivability makes shiitake mushrooms one of the most consumed edible fungi across global food systems.

Despite their global culinary appeal, fresh Shiitake mushrooms face significant postharvest challenges due to their high moisture content and fragile cellular structure. These inherent traits accelerate enzymatic and microbial activity, triggering rapid quality degradation through nutrient loss, texture softening, and a shortened shelf life [9, 10]. Conventional preservation approaches exhibit critical limitations: refrigeration incurs high energy costs without fully inhibiting spoilage; chemical treatments risk generating toxic residues and altering sensory profiles; drying processes degrade heat-sensitive nutrients and promote texture collapse, while improper storage of dried products facilitates moisture reabsorption and fungal proliferation [11, 12]. Non-thermal technologies that strike a balance between efficacy and sustainability are increasingly being prioritized to address these constraints. Emerging solutions, such as ozone treatment [13], coatings [14], pulsed electric fields [15], and gamma irradiation, demonstrate promise in extending shelf life while minimizing chemical inputs [16]. Among these,

ultraviolet irradiation is a green alternative [17]; its non-residual nature and energy efficiency align with consumer demand for safe, eco-friendly food processing methods.

Ultraviolet (UV) radiation spans the 100–400 nm wavelength range within the electromagnetic spectrum, comprising three subcategories: UV-A (320–400 nm), UV-B (280–320 nm), and UV-C (200–280 nm) [18]. Wavelengths between 250 and 280 nm have been shown to exhibit peak germicidal efficacy, with UV-C irradiation achieving microbial inactivation through direct DNA damage, specifically via the formation of pyrimidine dimer [19]. Beyond pathogen control, controlled UV-C exposure enhances plant defense mechanisms in postharvest produce by activating antioxidant enzymes and upregulating phenolic biosynthesis pathways [20–22]. These dual effects explain its widespread adoption in commercial storage systems, which maintain the nutritional integrity, chromatic stability, and textural properties of fruits and vegetables [23–25].

Recent studies have highlighted the efficacy of UV-C irradiation in postharvest preservation of mushrooms [26]. UV-C irradiation effectively inhibits browning and improves the postharvest quality of edible mushrooms, including button mushrooms, apricot mushrooms, and himematsutake mushrooms [21, 27, 28]. While these findings confirm the efficacy of UV-C in preservation, achieving consistent outcomes requires precise dose optimization to ensure optimal results. UV-C treatment at 8 KJ/m^2 actively suppresses phenylalanine ammonia-lyase (PAL) activity in fresh lettuce stems while maximizing chromatic stability – a critical quality parameter for leafy vegetables [29]. Elevated UV-C effectively combats fungal proliferation and Staphylococcus contamination without compromising fruit integrity [30]. Conversely, controlled low-intensity UV-C exposure enhances the synthesis of bioactive compounds in date palms, resulting in increased polyphenol concentrations and corresponding antioxidant capacity [31]. This dose-response dichotomy underscores the necessity of tailoring irradiation protocols to achieve both microbial safety and phytochemical enrichment in commercial postharvest systems.

The global ban on mercury-containing products under the Minamata Convention (effective after 2020) has driven an urgent demand for alternative UV light sources to replace low-pressure mercury lamps [32]. Recent advancements in UV-C technology prioritize mercury-free UV light-emitting diodes (LEDs), enabling precise tunability of wavelengths, achieving superior energy efficiency, and eliminating mercury contamination risks. Researchers and industry have increasingly adopted LED-UV systems for postharvest preservation of fresh produce and innovative food processing applications, demonstrating their potential to revolutionize sustainable food safety interventions [33–36].

Despite these advances in edible mushroom preservation, research on the dose-dependent effects of UV-C on shiitake mushrooms remains limited. Systematic optimization of irradiation parameters is crucial for balancing microbial control and sensory quality in commercial applications. This study evaluates the postharvest quality of fresh shiitake mushrooms treated with LED-generated UV-C irradiation at varying doses. We aim to identify the optimal LED-UV-C dose for maintaining nutritional attributes, color stability, and shelf life during storage. While previous studies predominantly relied on

mercury lamps, our work pioneers eco-friendly LED UV-C technology, addressing regulatory mandates and sustainable food processing requirements.

2. Materials and Methods

2.1 Materials

Fresh shiitake mushrooms were procured from Shaanxi Lueyang Keming Agricultural Development Co., Ltd. (Hanzhong, Shaanxi, China). We selected specimens of uniform size, free from physical defects and microbial contamination, and stored them at 4°C until processing.

2.2 LED-UV-C treatment

Fresh shiitake mushroom samples (2,000 g) with pileus diameters of 6 cm were prepared by removing the basal 2–3 cm of stipes. Samples were irradiated using an XL-UV001 multi-spectral UV incubator (Qingdao Jingyuan Fanguang Innovation Technology Co., Ltd.) equipped with 275 nm LED UV sources at an intensity of 39.17 μW/cm². Three irradiation durations were applied: 17, 34, and 68 min, corresponding to doses of 0.67, 1.33, and 2.66 kJ/m², respectively. During irradiation, mushrooms were rotated every 8.5 min to ensure uniform exposure. Untreated mushrooms served as controls. All treatment groups were separately sealed in polyethylene (PE) bags and stored at 4°C. Quality parameters were analyzed every 3 days, with three replicates per treatment.

2.2.1 Colorimetric Browning Analysis

We quantified color parameters L^* (light/dark), a^* (red/green), and b^* (yellow/blue) using an NR110 high-precision colorimeter (Shenzhen 3nh Technology Co., Ltd.) at 3-day intervals (0, 3, 6, 9, 12, 15, 18, and 21 d) to assess UV-C-induced browning. ΔE values were calculated relative to day 0 baselines (L_0^*, a_0^*, b_0^*), with increasing ΔE values directly correlating to browning severity. Three biological replicates per treatment group were analyzed [12].

$$\Delta \mathrm{E} = \sqrt{(L^* - {L_0}^*) + (a^* - {a_0}^*) + (b^* - {b_0}^*)}$$

2.2.2 Gravimetric Assessment

Physiological loss in weight (PLW) was quantified using a JA5003 analytical balance (precision of 0.001 g, Shanghai Hengping Instrument Co., Ltd.) by measuring the mass differential between the initial and each storage phase [37].

$$\mathrm{PLW}\,(\%) = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100\%$$

2.2.3 Determination of soluble protein content

We determined the soluble protein content using the Coomassie Brilliant Blue G-250 methodology [38]. We prepared homogenates by grinding 2.0 g of mushroom tissue with 5 mL of distilled water, followed by centrifuging the slurry at 18,353 × g for 20 min at 4°C (Centrifuge 5810 R, Eppendorf AG, Germany). We collected supernatants as soluble protein extracts and cryopreserved them. For analysis, we mixed 1.0 mL of the extract with 5.0 mL of Coomassie Brilliant Blue G-250 reagent, vortexed the solution, and incubated it for 2 minutes. We measured absorbance at 595 nm against a blank and calculated concentrations using standard curves of bovine serum albumin. All measurements were performed in triplicate.

2.2.4 Determination of flavonoid content

We determined the flavonoid content following a published method [39]. We prepared homogenates by grinding 2.0 g of mushroom tissue with 5 mL of distilled water, followed by centrifuging the slurry at 18,353 × g for 20 min at 4°C (Centrifuge 5810 R, Eppendorf AG, Germany). We collected the supernatant as a flavonoid extract and stored it at 4°C. For analysis, we mixed 1.0 mL of extract with 6.0 mL 70% v/v ethanol and 1.0 mL 5% m/v $NaNO_2$ solution. After 6 minutes of incubation, we added 1.0 mL of a 10% m/v $Al(NO_3)_3$ solution, vortex-mixed the sample, and then incubated it for another 6 minutes. We then introduced 10.0 mL of 4% m/v NaOH, adjusted the volume to 25 mL with 70% ethanol, vortex-mixed the solution, and measured the absorbance at 510 nm after a final 6-minute reaction against quercetin standard curves. We performed all measurements in triplicate.

2.2.5 Determination of total phenol content

We quantified total phenolic content using the Folin-Ciocalteu colorimetric method [40]. We prepared homogenates by grinding 2.0 g of mushroom tissue with 5 mL of distilled water, followed by centrifuging the slurry at 18,353 × g for 20 min at 4°C (Centrifuge 5810 R, Eppendorf AG, Germany). After collecting the supernatant as a polyphenol extract, we cryopreserved it. For analysis, we diluted 0.2 mL of the extract to 0.8 mL with distilled water, added 0.3 mL of 1 mol/L Folin-Ciocalteu reagent, and mixed thoroughly. The solution was then incubated in the dark for 8 min. We then introduced 0.6 mL of 10% w/v Na_2CO_3 solution, reacted the mixture for 30 minutes at 25°C, protected from light, and adjusted the volume to 25 mL. We measured absorbance at 750 nm against a reagent blank and calculated concentrations using gallic acid standard curves. Each treatment was replicated three times.

2.2.6 Determination of reducing sugar content

We quantified reducing sugar content using the 3,5-dinitrosalicylic acid (DNS) method [41]. We prepared homogenates by grinding 1.0 g of mushroom tissue with 10 mL of distilled water, followed by centrifuging the slurry at 18,353 × g for 20 min at 4°C (Centrifuge 5810 R, Eppendorf AG, Germany), and collecting the supernatant. We incubated the extract for 30 min in an 80°C constant-temperature water bath to liberate reducing sugars. After cooling, we transferred the extract to a 10 mL volumetric flask, brought it to volume, and cryopreserved it. For analysis, we combined 2.0 mL of extract with 1.5 mL of DNS reagent in a 25 mL volumetric flask, mixed thoroughly, heated the solution in boiling water for 5 min,

cooled it to ambient temperature, and measured absorbance spectrophotometrically at 540 nm. We calculated concentrations using glucose standard curves. Each treatment was replicated three times.

2.2.7 Determination of free amino acid content

We quantified total free amino acids via ninhydrin colorimetry [8]. We prepared homogenates by grinding 1.0 g of mushroom tissue with 5.0 mL 10% v/v acetic acid and 5.0 mL distilled water, followed by centrifuging the slurry at 18,353 × g for 20 min at 4°C (Centrifuge 5810 R, Eppendorf AG, Germany), and transferring the supernatant to a 100-mL volumetric flask. We adjusted the extract to volume with distilled water and cryopreserved it. For analysis, we combined 1.0 mL of the extract with 1.0 mL of distilled water, 3.0 mL of ninhydrin reagent, and 0.1 mL of ascorbic acid in a 20-mL sealed test tube. After vortexing vigorously, the mixture was heated in a boiling water bath for 15 minutes, cooled under running water, and then 5.0 mL of 95% (v/v) ethanol was added, followed by re-vortexing. We then diluted the solution to 20 mL with 60% (v/v) ethanol and measured absorbance at 570 nm against a reagent blank. Each treatment was replicated three times.

2.2.8 PPO Activity Measurement

We determined PPO activity using the catechol assay [42]. We prepared homogenates by grinding 2.0 g of mushroom tissue with 5.0 mL of extraction buffer in an ice bath. The slurry was then centrifuged at 18,353 × g for 20 min at 4°C (Centrifuge 5810 R, Eppendorf AG, Germany), and the supernatant was collected as the enzyme extract for cryopreservation. For kinetic analysis, we combined 4.0 mL of 50 mmol/L acetate buffer (pH 5.5) with 1.0 mL of 50 mmol/L catechol solution in a test tube, initiated the reaction by adding 200 µL of enzyme extract, and immediately began timing. Using distilled water as a reference, we recorded the initial absorbance at 420 nm after 15 seconds and performed consecutive measurements at 30-second intervals for a total of six readings. We conducted triplicate assays per treatment.

2.2.9 POD Activity Measurement

We determined POD activity using the guaiacol oxidation method [42]. We prepared homogenates by grinding 2.0 g of mushroom tissue with 5.0 mL of extraction buffer in an ice bath, followed by centrifugation of the slurry at 18,353 × g for 20 min at 4°C (Centrifuge 5810 R, Eppendorf AG, Germany). The supernatant was then collected as the enzyme extract for cryopreservation. For kinetic analysis, we combined 3.0 mL of a 25 mmol/L guaiacol solution with 0.5 mL of enzyme extract in a test tube, added 200 µL of 0.5 mol/L H_2O_2, and then vortexed vigorously. The timing was immediately initiated. We recorded the initial absorbance at 470 nm after 15 seconds against a distilled water reference and performed consecutive measurements at 30-second intervals for six readings. We conducted triplicate assays per treatment.

2.2.10 PAL Activity Measurement

We determined PAL activity using the L-phenylalanine method [43]. We prepared homogenates by grinding 2.0 g of mushroom tissue with 5.0 mL extraction buffer in an ice bath using a mortar and pestle,

followed by centrifuging the slurry at 18,353 × g for 20 min at 4°C (Centrifuge 5810 R, Eppendorf AG, Germany), and collected the supernatant as enzyme extract for cryopreservation. For analysis, we prepared two test tubes, each containing 3.0 mL 50 mmol/L borate buffer and 0.5 mL 25 mmol/L L-phenylalanine solution. We added 0.5 mL of enzyme extract to the sample tube and 0.5 mL of heat-inactivated enzyme (boiled for 5 minutes) to the control tube. We incubated both tubes at 37°C for 60 minutes, terminated the reactions by adding 0.1 mL of 6 mol/L HCl, vortexed vigorously, and measured the absorbance at 290 nm against a distilled water reference for both solutions. We conducted triplicate assays per treatment.

2.2.11 Microbiological analysis

We performed microbiological analysis in accordance with GB 4789.2–2022 (National Food Safety Standard: Enumeration of Colony Count). Samples were plated on standard plate count agar (PCA), incubated at 36 ± 1°C for 48 ± 2 h, and enumerated for total viable colonies.

2.2.12 Sensory Analysis

Ethical approval for this study was granted by the Research Ethics Committee of Shaanxi University of Technology (Approval No. 2025061601), and written informed consent was obtained from all participants before sensory evaluation. Both UV-treated and control shiitake mushroom samples were assessed at 3-day intervals over a 21-day storage period (days 0, 3, 6, 9, 12, 15, 18, 21) by a gender-balanced panel of ten trained food science students. Evaluations were performed in triplicate at each time point using a 9-point hedonic scale (1 = strongly dislike, 9 = strongly like) for the following attributes: Appearance: Samples exhibiting plump caps, closed veils, and no wilting were assigned 7–9 points; those with slight cap collapse or wilting received 4–6 points; severely wilted samples or those with fully opened veils were scored 1–3 points. Color: Samples displaying normal color with white gills were rated 7–9 points; those showing slight browning or darkening were given 4–6 points; samples exhibiting severe discoloration were assigned 1–3 points. Odor: Samples possessing a pronounced shiitake-specific aroma were scored 7–9 points; those with a faint aroma received 4–6 points; samples presenting distinct undesirable off-odors were assigned 1–3 points.

2.3 Statistical analysis

Statistical analyses were performed using SPSS 27.0 software. All measurements were conducted in triplicate. A two-way analysis of variance was employed to assess the effects of dose and storage time as independent variables on each parameter. Significant differences among means were determined by Duncan's multiple range test at a significance level of $p < 0.05$. Graphical representations were generated using GraphPad Prism 10.1.2 software.

3. Results and Discussion

3.1 Color

ΔE serves as an objective indicator of color changes in shiitake mushrooms during storage [3]. Browning in these mushrooms is primarily caused by the oxidation of phenolic compounds, a process catalyzed by enzymes such as PPO [44]. As shown in Fig. 1, both UV-C-treated and control samples exhibit progressive darkening throughout storage. Higher UV-C doses correspond to greater ΔE values ($p < 0.05$), indicating progressive darkening. Notably, shiitake mushrooms treated with 0.67 kJ/m² maintained color stability comparable to the control ($p > 0.05$) throughout storage, with lower ΔE observed specifically at days 15 and 18. In contrast, shiitake mushrooms treated with 1.33 and 2.66 kJ/m² UV-C exhibit higher ΔE values than the control ($p < 0.05$). This dose-dependent effect indicates that increased UV-C irradiation intensity intensified browning development in shiitake mushrooms. Similarly, low-dose UV-C irradiation activated defense enzyme activity. It also elevated the synthesis of antioxidant compounds and phenolic substances in white button mushrooms, thereby delaying the development of browning [20].

3.2 Weight loss

Weight loss in shiitake mushrooms during postharvest storage was primarily caused by respiratory metabolism and moisture evaporation, leading to quality deterioration [1]. As shown in Fig. 2, all treatment groups exhibit progressive weight loss with extended storage duration. No differences ($p > 0.05$) were observed among treatments at any given storage interval. However, the control group exhibits the highest cumulative weight loss (13.71% of the initial mass), while UV-C treatments at 0.67, 1.33, and 2.66 kJ/m² result in reduced losses of 10.70%, 9.43%, and 8.47%, respectively. These results indicate that UV-C irradiation effectively attenuates weight loss in a dose-dependent manner, with higher irradiation doses exhibiting stronger preservation effects.

3.3 Proteins and free amino acids

Protein content serves as a critical physiological and biochemical indicator in shiitake mushrooms, reflecting their nutritional quality and postharvest status. As a key substrate in metabolic processes, protein degradation has a direct influence on mushroom quality [45]. As shown in Fig. 3a, soluble protein content in all treatment groups declined throughout storage. Notably, mushrooms treated with UV-C at 0.67 kJ/m² retained higher protein levels than the control group over the entire storage period ($p < 0.05$). In contrast, doses of 1.33 and 2.66 kJ/m² resulted in lower soluble protein content relative to the control ($p < 0.05$). By day 21 of storage, the soluble protein content in the control, 0.67, 1.33, and 2.66 kJ/m² treatment groups corresponded to 30.18%, 49.13%, 27.52%, and 0.46% of their initial values, respectively. These results demonstrate that treatment with 0.67 kJ/m² UV-C effectively delayed the degradation of soluble proteins, thereby contributing to the maintenance of postharvest quality in shiitake mushrooms.

Amino acids serve as the fundamental units of proteins and represent one of the primary degradation products of protein metabolism. Free amino acids are closely associated with quality attributes and characteristic flavor profiles in fruits and vegetables [46]. Fluctuations in free amino acid content reflect physiological and biochemical metabolic activity during growth, development, ripening, and senescence. As illustrated in Fig. 3b, changes in amino acid content in shiitake mushrooms treated with varying UV-C

doses throughout storage are presented. A consistent trend of initial increase followed by a decrease was observed across all groups. The time to peak amino acid content, however, varied among treatments. Mushrooms treated with 0.67 and 2.66 kJ/m² UV-C reached maximum values on day 6, with concentrations of 37.72 μg/g and 54.63 μg/g, respectively. In contrast, the control group and those treated with 1.33 kJ/m² attained peak levels on day 9, registering 51.03 μg/g and 29.12 μg/g, respectively. Following these peaks, a progressive decline in amino acid content occurred. By day 21 of storage, the amino acid contents in the control, 0.67, 1.33, and 2.66 kJ/m² treatment groups measured 22.74 μg/g, 8.04 μg/g, 6.94 μg/g, and 9.43 μg/g, respectively. Notably, the control group exhibited higher amino acid retention compared to all UV-treated groups ($p < 0.05$). These results indicate that UV-C irradiation can induce a transient increase in free amino acid content during early storage, thereby partially mitigating quality deterioration in shiitake mushrooms.

3.4 Changes in Bioactive Compounds and Sugar Content

Flavonoids present in shiitake mushrooms are bioactive compounds with potential health-promoting properties. Flavonoids are known for their antioxidant activity, which contributes to delaying senescence during storage [47, 48]. As illustrated in Fig. 4a, the flavonoid content in both UV-C-treated and control groups initially increased, followed by a gradual decrease during storage, reaching a peak on day 6. On that day, the flavonoid contents in the control, 0.67, 1.33, and 2.66 kJ/m² treatment groups were 64.04 μg/g, 59.75 μg/g, 66.06 μg/g, and 33.48 μg/g, respectively. No difference was observed between the 0.67 kJ/m² treatment group and the control ($p > 0.05$). Similarly, the 1.33 kJ/m² treatment did not differ from the control ($p > 0.05$), although it resulted in notably higher flavonoid content compared to the 0.67 kJ/m² group ($p < 0.05$). In contrast, the 2.66 kJ/m² treatment led to lower flavonoid levels than all other groups throughout the storage period ($p < 0.05$). Beyond day 6, a consistent decline in flavonoid content was observed across all treatments.

Phenolic compounds play a critical role in determining the visual quality and market value of shiitake mushrooms [49]. As depicted in Fig. 4b, UV-C irradiation at varying doses influenced the phenolic content, which initially increased and subsequently decreased during storage across all treatment groups. From day 0 to day 9, a consistent accumulation of phenolic compounds was observed, culminating in peak values on day 9. The corresponding phenolic contents in the control, 0.67, 1.33, and 2.66 kJ/m² treatment groups were 91.42 μg/g, 86.55 μg/g, 89.13 μg/g, and 75.19 μg/g, respectively. Notably, the phenolic levels in the control, 0.67 kJ/m², and 1.33 kJ/m² groups were higher than those in the 2.66 kJ/m² group ($p < 0.05$). Upon prolonged storage, a gradual decline in phenolic content occurred. By day 21, the residual phenolic content relative to the initial values was 66.18% in the control group, 64.00% in the 0.67 kJ/m² group, 64.79% in the 1.33 kJ/m² group, and 87.33% in the 2.66 kJ/m² group. These results indicate that UV-C treatment at 2.66 kJ/m² effectively preserved phenolic compounds in shiitake mushrooms throughout storage, highlighting its potential for maintaining product quality.

Reducing sugars in fruits and vegetables are primarily derived from the degradation of polysaccharides and other macromolecules. These sugars also serve as crucial glycosyl donors for the biosynthesis of various fungal metabolites, including glycogen, trehalose, and cell wall polysaccharides such as chitin

and β-glucans, thereby playing an integral role in postharvest physiological and metabolic processes[50–52]. As illustrated in Fig. 4c, UV-C irradiation at varying doses affected the reducing sugar content in shiitake mushrooms during storage. A consistent decreasing trend was observed in all treatment groups ($p < 0.05$). On day 0, the reducing sugar contents in the control, 0.67, 1.33, and 2.66 kJ/m² treatment groups were 2.37 mg/g, 2.72 mg/g, 3.02 mg/g, and 1.45 mg/g, respectively, with statistically significant differences among groups ($p < 0.05$). Throughout the storage period, mushrooms treated with 0.67 and 1.33 kJ/m² UV-C maintained higher reducing sugar levels compared to the control group, whereas those treated with 2.66 kJ/m² exhibited consistently lower values. All pairwise comparisons between treatment groups showed differences ($p < 0.05$), suggesting a dose-dependent response of carbohydrate metabolism to UV-C stress.

3.5 Metabolic enzyme activity

PPO catalyzes the oxidation of various monophenols into quinones, which subsequently polymerize to form brown, dark brown, or black pigments. Tissue browning in fruits and vegetables, often occurring during postharvest storage, processing, or ripening, is closely associated with PPO activity [15]. As shown in Fig. 5a, PPO activity in shiitake mushrooms followed a trend of initial increase followed by gradual decrease throughout storage across all treatment groups. Peak activity was observed on day 9 in all four groups. Notably, the group treated with 1.33 kJ/m² UV-C exhibited higher PPO activity at this time point compared to other doses ($p < 0.05$). Compared to the control group, treatments with 0.67 kJ/m² and 1.33 kJ/m² UV-C maintained higher PPO activity throughout the storage period. In contrast, mushrooms treated with 2.66 kJ/m² UV-C showed higher PPO activity than the control during the first 6 days, but lower activity from day 9 onward. These results suggest that UV-C treatment at a dose of 2.66 kJ/m² effectively suppresses PPO activity in shiitake mushrooms.

POD is a crucial oxidoreductase widely present in fruits and vegetables, involved in numerous physiological and metabolic processes. Its activity dynamically changes throughout growth, development, ripening, and senescence, and responds to various external stimuli such as storage conditions and processing treatments [53]. As shown in Fig. 5b, POD activity in UV-C-treated shiitake mushrooms exhibited an initial increase followed by a decrease throughout storage, regardless of dosage. Compared to the control group, the 0.67 kJ/m² treatment maintained higher POD activity for most of the storage period, although it decreased below the control level by day 21. The 1.33 kJ/m² treatment resulted in the highest POD activity among all groups throughout the entire storage period.

In contrast, the 2.66 kJ/m² treatment led to higher POD activity than the control from day 0 to day 6 and on day 18, but lower activity from day 9 to day 15 and on day 21. These results suggest that UV-C treatments at 0.67 and 1.33 kJ/m² effectively maintained higher antioxidant enzyme activity, thereby contributing to improved quality of shiitake mushrooms. The most favorable effects were observed with the 1.33 kJ/m² dose.

PAL is a key enzyme in the biosynthesis of numerous secondary metabolites in plants and is closely associated with stress response and disease resistance. It plays an essential role in normal growth,

development, and defense against pathogen attacks [53]. PAL is directly associated with the synthesis of phenolic compounds in cells and is also an antioxidant enzyme involved in the biosynthesis of secondary metabolites [54]. As shown in Fig. 5c, PAL activity in shiitake mushrooms decreased over storage time across all UV-C treatment doses ($p < 0.05$). The reductions in PAL activity by the end of storage were 94.64% in the control group, and 88.11%, 84.94%, and 96.06% in the 0.67, 1.33, and 2.66 kJ/m² treatment groups, respectively. UV-C treatment at 0.67 and 1.33 kJ/m² delayed the decline in PAL activity, with the most effective preservation observed at 1.33 kJ/m².

In contrast, the 2.66 kJ/m² treatment accelerated the loss of PAL activity compared to the control. Maintaining higher PAL activity during storage helps reduce quality deterioration in shiitake mushrooms. In this study, treatments at 0.67 and 1.33 kJ/m² effectively sustained higher PAL activity, thereby contributing to better preservation of mushroom quality. The most favorable outcome was achieved with the 1.33 kJ/m² dose. Therefore, low-dose irradiation can influence the enzyme activities of shiitake mushrooms and, to a certain extent, extend their shelf life [55].

3.6 Microbial evaluation

The rapid proliferation of microorganisms in shiitake mushroom fruiting bodies during storage accelerates decay and tissue deterioration, thereby compromising product quality [33]. UV-C irradiation inactivates microorganisms by inducing the formation of cyclobutane pyrimidine dimers and other photolesions in microbial DNA, leading to irreversible damage and loss of viability [56]. As shown in Fig. 6, the total viable count increased continuously during storage across all treatment groups. An increase was observed from day 0 to day 12 ($p < 0.05$), followed by a slower rate of increase after day 12 ($p > 0.05$). Throughout the storage period, the control group had higher microbial counts than all UV-C-treated groups ($p < 0.05$). On day 21, the total microbial counts in mushrooms treated with 0.67, 1.33, and 2.66 kJ/m² UV-C were reduced by 12.39%, 13.80%, and 14.71%, respectively, compared to the control. Notably, the group treated with 2.66 kJ/m² showed lower microbial counts than all other treatment groups ($p < 0.05$). These results confirm the sterilizing effect of UV-C treatment and demonstrate that higher irradiation doses provide more effective suppression of microbial proliferation in shiitake mushrooms.

3.7 Sensory Analysis

Odor, color, and morphology are critical indicators for evaluating the sensory quality of edible mushrooms. During storage of shiitake mushrooms, physiological and biochemical changes lead to browning, cap opening, loss of elasticity, and off-odor development [57]. As shown in Fig. 7, sensory scores of mushrooms treated with different UV-C doses progressively decreased during storage. Although the group treated with 0.67 kJ/m² UV-C received slightly higher sensory scores compared to other treatments, the differences were not statistically significant ($p > 0.05$). These results indicate that neither the control nor any of the three UV-C treatment doses had a substantial impact on the sensory attributes of the mushrooms ($p > 0.05$). In contrast, storage time exerted a more pronounced influence on sensory quality ($p < 0.05$).

4. Conclusions

This study systematically evaluates the effects of LED UV-C irradiation at different doses on the postharvest quality of fresh shiitake mushrooms. The results demonstrate that UV-C treatment effectively delayed quality deterioration during storage in a dose-dependent manner. The 2.66 kJ/m² UV-C treatment exhibited the most pronounced effects in inhibiting microbial growth, reducing weight loss, and retaining total phenolic content. The 0.67 kJ/m² treatment resulted in higher soluble protein and flavonoid levels. Meanwhile, the 1.33 kJ/m² treatment resulted in higher POD and PAL enzyme activities. Sensory attributes remained largely unaffected by UV-C treatments. In conclusion, LED UV-C treatment, particularly at 2.66 kJ/m², represents an efficient and environmentally friendly postharvest strategy that affects several quality parameters in shiitake mushrooms.

Declarations

Conflict of Interest

The authors declare no competing interests.

6. Funding

The authors would like to acknowledge the Shaanxi Provincial Education Department Service Local Special Project (25JC024), the Key Project of Agricultural Science and Technology of Shaanxi Province (2024NC-YBXM-185), the National College Student Innovation and Entrepreneurship Project (S202510720136), and Project of Qinba State Key Laboratory of Biological Resources and Ecological Environment (Incubation) (SXC-2302) for their financial support.

Author Contribution

Jie Du: Conceptualization, Methodology, Investigation, Writing-original draft. Yu Feng: Software, Formal analysis, Validation. Lina Chen: Investigation, Resources. Faushu Kong: Data curation, Visualization. Xu Yang: Methodology, Validation. Lina Meng: Resources, Data curation. Ching Yuan Hu: Writing-review editing, Supervision. Chen Xu: Investigation. Daihua Hu: Writing-review editing, Supervision, Funding acquisition.

References

1. Li, Y., S. Ding and Y. Wang, Shelf life predictive model for postharvest shiitake mushrooms. Journal of Food Engineering, 2022. 330: 111099.'https://doi.org/10.1016/j.jfoodeng.2022.111099'

2. Xu, L., et al., Effects of high-temperature pre-drying on the quality of air-dried shiitake mushrooms (Lentinula edodes). Food chemistry, 2019. 285: 406–413.'https://doi.org/10.1016/j.foodchem.2019.01.179'
3. Subramaniam, S., et al., Impact of post-harvest processing or thermal dehydration on physiochemical, nutritional and sensory quality of shiitake mushrooms. Comprehensive Reviews in Food Science and Food Safety, 2021. 20(3): 2560–2595.'https://doi.org/10.1111/1541-4337.12738'
4. dos Santos Harada-Padermo, S., et al., Umami Ingredient: Flavor enhancer from shiitake (Lentinula edodes) byproducts. Food Research International, 2020. 137: 109540.'https://doi.org/10.1016/j.foodres.2020.109540'
5. Papoutsis, K., et al., Recovery of ergosterol and vitamin D2 from mushroom waste-Potential valorization by food and pharmaceutical industries. Trends in Food Science & Technology, 2020. 99: 351–366.'https://doi.org/10.1016/j.tifs.2020.03.005'
6. Ahmad, I., et al., Therapeutic values and nutraceutical properties of shiitake mushroom (Lentinula edodes): A review. Trends in Food Science & Technology, 2023. 134: 123–135.'https://doi.org/10.1016/j.tifs.2023.03.007'
7. Royse, D.J., J. Baars and Q. Tan, Current overview of mushroom production in the world. Edible and medicinal mushrooms: technology and applications, 2017: 5–13.'https://doi.org/10.1002/9781119149446.ch2'
8. Huang, D., et al., A comprehensive metabolomics analysis of volatile and non-volatile compounds in matcha processed from different tea varieties. Food chemistry: X, 2024. 21: 101234.'https://doi.org/10.1016/j.fochx.2024.101234'
9. Abdelshafy, A.M., et al., A comprehensive review on preservation of shiitake mushroom (Lentinus edodes): techniques, research advances and influence on quality traits. Food Reviews International, 2023. 39(5): 2742–2775.'https://doi.org/10.1080/87559129.2021.1967381'
10. Liu, Q., et al., Comparison of different drying techniques for shiitake mushroom (Lentinus edodes): Changes in volatile compounds, taste properties, and texture qualities. Lwt, 2022. 164: 113651.'https://doi.org/10.1016/j.lwt.2022.113651'
11. Yang, W., et al., Effect of bound water on the quality of dried Lentinus edodes during storage. Journal of the Science of Food and Agriculture, 2020. 100(5): 1971–1979.'https://doi.org/10.1002/jsfa.10210'
12. Wang, Y., et al., Effectiveness of combined catalytic infrared radiation and holding time for decontamination Aspergillus niger on dried shiitake mushrooms (Lentinus edodes) with different moisture contents. LWT, 2023. 176: 114503.'https://doi.org/10.1016/j.lwt.2023.114503'
13. Niveditha, A., et al., Application of cold plasma and ozone technology for decontamination of Escherichia coli in foods-a review. Food control, 2021. 130: 108338.'https://doi.org/10.1016/j.foodcont.2021.108338'
14. Nasiri, M., et al., Application of Tragacanth gum impregnated with Satureja khuzistanica essential oil as a natural coating for enhancement of postharvest quality and shelf life of button mushroom

(Agaricus bisporus). International journal of biological macromolecules, 2018. 106: 218–226.'https://doi.org/10.1016/j.ijbiomac.2017.08.003'

15. Subrahmanyam, K., et al., Impact of in-package cold plasma treatment on the physicochemical properties and shelf life of button mushrooms (Agaricus bisporus). Food Bioscience, 2023. 52: 102425.'https://doi.org/10.1016/j.fbio.2023.102425'
16. Malik, M.A., et al., Enhancement of vitamin D2 in edible mushroom using ultraviolet irradiation and assessing its storage and cooking stability. Nutrition & Food Science, 2022. 52(8): 1254–1269.'https://doi.org/10.1108/NFS-12-2021-0391'
17. Guan, W., X. Fan and R. Yan, Effect of combination of ultraviolet light and hydrogen peroxide on inactivation of Escherichia coli O157: H7, native microbial loads, and quality of button mushrooms. Food Control, 2013. 34(2): 554–559.'https://doi.org/10.1016/j.foodcont.2013.05.027'
18. Al-Sadek, T. and N. Yusuf, Ultraviolet Radiation Biological and Medical Implications. Current Issues in Molecular Biology, 2024. 46(3): 1924–1942.'https://doi.org/10.3390/cimb46030126'
19. Harpreet, S., et al., UVC radiation for food safety: An emerging technology for the microbial disinfection of food products. Chemical Engineering Journal, 2020(prepublish): 128084-.'https://doi.org/10.1016/j.cej.2020.128084'
20. Wang, X., et al., UV-C treatment inhibits browning, inactivates Pseudomonas tolaasii and reduces associated chemical and enzymatic changes of button mushrooms. Journal of the Science of Food and Agriculture, 2022. 102(8): 3259–3265.'https://doi.org/10.1002/jsfa.11668'
21. Lu, Y., et al., Effects of UV-C irradiation on the physiological and antioxidant responses of button mushrooms (Agaricus bisporus) during storage. International Journal of Food Science and Technology, 2016. 51(6): 1502–1508.'https://doi.org/10.1111/ijfs.13100'
22. Lei, J., et al., Effects of UV-C treatment on browning and the expression of polyphenol oxidase (PPO) genes in different tissues of Agaricus bisporus during cold storage. Postharvest Biology and Technology, 2018. 139: 99–105.'https://doi.org/10.1016/j.postharvbio.2017.11.022'
23. Zhou, D., et al., Hot air and UV-C treatments promote anthocyanin accumulation in peach fruit through their regulations of sugars and organic acids. Food Chemistry, 2020. 309: 125726.'https://doi.org/10.1016/j.foodchem.2019.125726'
24. Zhang, Q., et al., Postharvest UV-C irradiation increased the flavonoids and anthocyanins accumulation, phenylpropanoid pathway gene expression, and antioxidant activity in sweet cherries (Prunus avium L.). Postharvest Biology and Technology, 2021. 175: 111490.'https://doi.org/10.1016/j.postharvbio.2021.111490'
25. Rabelo, M.C., et al., UVC light modulates vitamin C and phenolic biosynthesis in acerola fruit: Role of increased mitochondria activity and ROS production. Scientific Reports, 2020. 10(1): 21972.'https://doi.org/10.1038/s41598-020-78948-1'
26. Feng, Y., et al., Effect of light on quality of preharvest and postharvest edible mushrooms and its action mechanism: A review. Trends in Food Science & Technology, 2023. 139: 104119.'https://doi.org/10.1016/j.tifs.2023.104119'

27. Wang, Q., L. Chu and L. Kou, UV-C Treatment maintains quality and delays senescence of oyster mushroom (Pleurotus ostreatus). Scientia Horticulturae, 2017. 225: 380–385.'https://doi.org/10.1016/j.scienta.2017.07.019'
28. Nunes, M.P.C., et al., Postharvest of fresh white shimeji mushroom subjected to UV-C radiation. Heliyon, 2024. 10(3).'https://doi.org/10.1016/j.heliyon.2024.e25115'
29. Han, C., et al., UV-C irradiation inhibits surface discoloration and delays quality degradation of fresh-cut stem lettuce. LWT, 2021. 147: 111533.'https://doi.org/10.1016/j.lwt.2021.111533'
30. Sánchez, G.J., et al., Study of UV-C treatments on postharvest life of blueberries 'O'Neal'and correlation between structure and quality parameters. Heliyon, 2021. 7(6).'https://doi.org/10.1016/j.heliyon.2021.e07190'
31. Dassamiour, S., et al., Effect of postharvest UV-C radiation on nutritional quality, oxidation and enzymatic browning of stored mature date. Applied Sciences, 2022. 12(10): 4947.'https://doi.org/10.3390/foods11050653'
32. Hsu, T.-C., et al., Perspectives on UVC LED: Its Progress and Application. Photonics, 2021. 8(6): 196.'https://doi.org/10.3390/photonics8060196'
33. Darré, M., et al., Postharvest ultraviolet radiation in fruit and vegetables: Applications and factors modulating its efficacy on bioactive compounds and microbial growth. Foods, 2022. 11(5): 653.'https://doi.org/10.3390/foods11050653'
34. Baykuş, G., M.P. Akgün and S. Unluturk, Effects of ultraviolet-light emitting diodes (UV-LEDs) on microbial inactivation and quality attributes of mixed beverage made from blend of carrot, carob, ginger, grape and lemon juice. Innovative Food Science & Emerging Technologies, 2021. 67: 102572.'https://doi.org/10.1016/j.ifset.2020.102572'
35. Singh, H., et al., UVC radiation for food safety: An emerging technology for the microbial disinfection of food products. Chemical Engineering Journal, 2021. 417: 128084.'https://doi.org/10.1016/j.cej.2020.128084'
36. Nassarawa, S.S., et al., *Effect of light-emitting diodes (LEDs) on the quality of fruits and vegetables during postharvest period: a review. Food Bioprocess Technol 14: 388–414*. 2021.
37. Menaka, M., et al., UV-C irradiation enhances the quality and shelf-life of stored guava fruit via boosting the antioxidant systems and defense responses. Food and Bioprocess Technology, 2024. 17(11): 3704–3715.'https://doi.org/10.1007/s11947-024-03338-8'
38. Spector, T., Refinement of the Coomassie blue method of protein quantitation: a simple and linear spectrophotometric assay for ≤ 0.5 to 50 µg of protein. Analytical biochemistry, 1978. 86(1): 142–146.'https://doi.org/10.1016/0003-2697(78)90327-5'
39. Meng Ge, M.G., et al., Antioxidant activities of medicinal fungus Ganoderma lingzhi in the process of liquid cultivation. 2018.'https://doi.org/10.13346/j.mycosystema.170230'
40. Singleton, V.L., R. Orthofer and R.M. Lamuela-Raventós, *[14] Analysis of total phenols and other oxidation substrates and antioxidants by means of folin-ciocalteu reagent*, in *Methods in enzymology*. 1999, Elsevier. p. 152–178.

41. Jain, A., R. Jain and S. Jain, *Quantitative analysis of reducing sugars by 3, 5-dinitrosalicylic acid (DNSA method)*, in *Basic Techniques in Biochemistry, Microbiology and Molecular Biology: Principles and Techniques*. 2020, Springer. p. 181–183.
42. Tarafdar, A., B.P. Kaur and S. Pareek, Effect of microfluidization on deteriorative enzymes, sugars, chlorophyll, and color of sugarcane juice. Food and Bioprocess Technology, 2021. 14: 1375–1385.'https://doi.org/10.1007/s11947-021-02651-w'
43. Manda-Hakki, K. and H. Hassanpour, Changes in Postharvest Quality and Physiological Attributes of Strawberry Fruits Influenced by l-Phenylalanine. Food Science & Nutrition, 2024. 12(12): 10262–10274.'https://doi.org/10.1002/fsn3.4564'
44. Im, J.-H., et al., Phenylalanine ammonia-lyase: A key gene for color discrimination of edible mushroom Flammulina velutipes. Journal of Fungi, 2023. 9(3): 339.'https://doi.org/10.3390/jof9030339'
45. Yang, Y., et al., The influences of X-rays irradiation on sensory attributes and physicochemical properties of shiitake mushrooms during storage. Journal of Stored Products Research, 2025. 111: 102500.'https://doi.org/10.1016/j.jspr.2024.102500'
46. Chen, D., et al., Dynamic changes and formation of key contributing odorants with amino acids and reducing sugars as precursors in shiitake mushrooms during hot air drying. Food Chemistry, 2023. 424: 136409.'https://doi.org/10.1016/j.foodchem.2023.136409'
47. Kopustinskiene, D.M., et al., Flavonoids as anticancer agents. Nutrients, 2020. 12(2): 457.'https://doi.org/10.3390/nu12020457'
48. Wang, S., et al., Mushrooms do produce flavonoids: metabolite profiling and transcriptome analysis of flavonoid synthesis in the medicinal mushroom Sanghuangporus baumii. Journal of fungi, 2022. 8(6): 582.'https://doi.org/10.3390/jof8060582'
49. Abdelshafy, A.M., et al., A comprehensive review on phenolic compounds from edible mushrooms: Occurrence, biological activity, application and future prospective. Critical Reviews in Food Science and Nutrition, 2022. 62(22): 6204–6224.'https://doi.org/10.1080/10408398.2021.1898335'
50. Newman, Y., S. Ring and C. Colaco, The role of trehalose and other carbohydrates in biopreservation. Biotechnology and genetic engineering reviews, 1993. 11(1): 263–294
51. Patyshakuliyeva, A., et al., Carbohydrate utilization and metabolism is highly differentiated in Agaricus bisporus. BMC genomics, 2013. 14(1): 663
52. Li, Y., et al., Exogenous trehalose increased polysaccharide content and altered their properties and metabolism in Lentinula edodes mycelium. International Journal of Biological Macromolecules, 2025: 143387
53. Liu, Q., et al., Coating shiitake mushrooms (Lentinus edodes) with a polysaccharide from Oudemansiella radicata improves product quality and flavor during postharvest storage. Food Chemistry, 2021. 352: 129357.'https://doi.org/10.1016/j.foodchem.2021.129357'
54. Yu, J., N.J. Engeseth and H. Feng, High intensity ultrasound as an abiotic elicitor—effects on antioxidant capacity and overall quality of romaine lettuce. Food and Bioprocess Technology, 2016.

9(2): 262–273.'https://doi.org/10.1007/s11947-015-1616-7'

55. Zhong, Y., et al., Recent advances in postharvest irradiation preservation technology of edible fungi: A review. Foods, 2022. 12(1): 103.'https://doi.org/10.3390/foods12010103'
56. Livneh, Z., et al., Replication of damaged DNA and the molecular mechanism of ultraviolet light mutagenesis. Critical reviews in biochemistry and molecular biology, 1993. 28(6): 465–513.'https://doi.org/10.3109/10409239309085136'
57. Shuaiping, G., et al., Effects of two kinds of modified atmosphere preservation methods on storage quality and physiological and biochemical properties of Lentinus edodes. Science and Technology of Food Industry, 2021. 42(4): 276–281.'https://dx.doi.org/10.13386/j.issn1002-0306.2020040042'

Figures

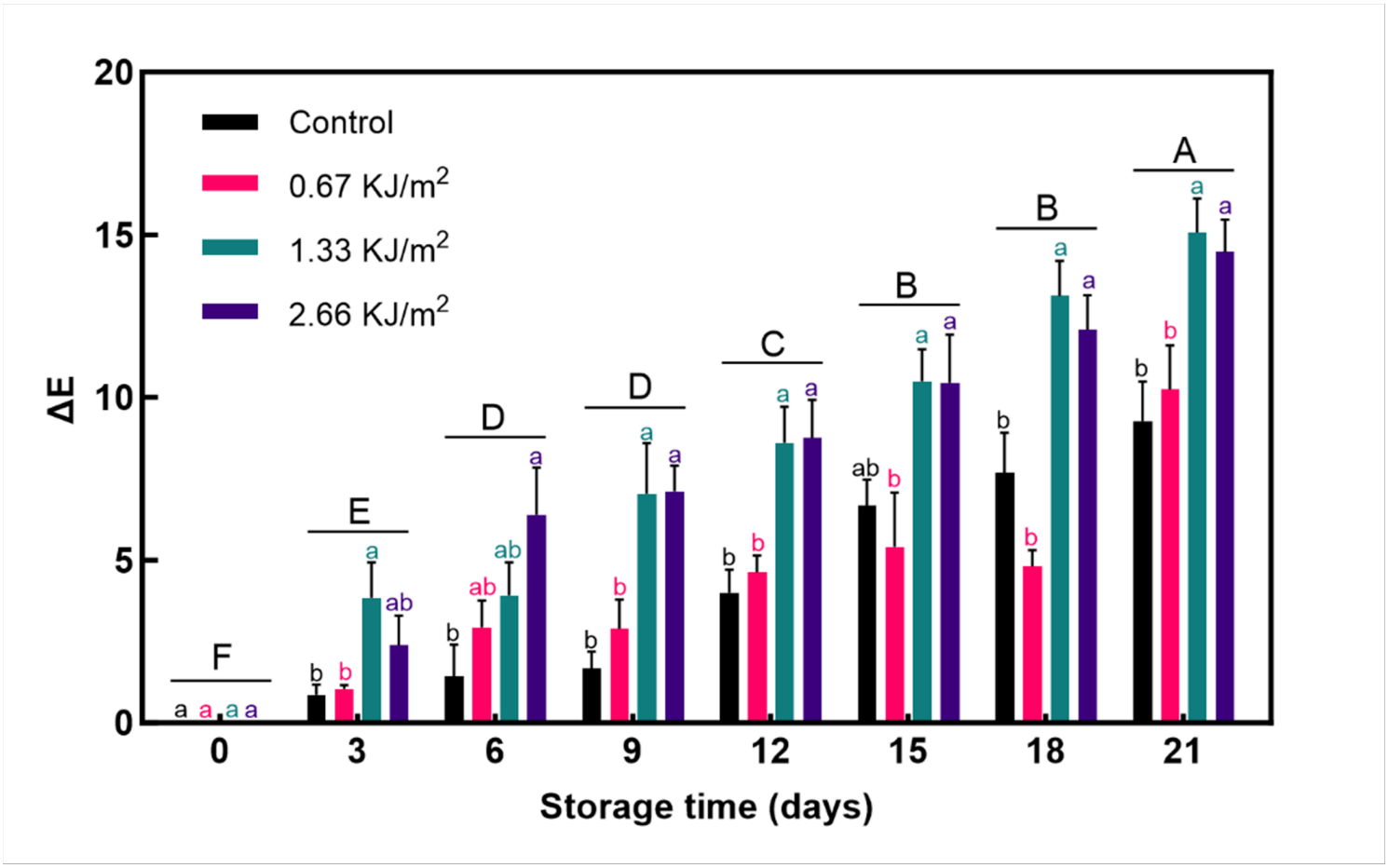

Figure 1

Dose-dependent effects of UV-C treatment on color difference (ΔE) of shiitake mushrooms during storage. Different capital letters indicate differences ($p < 0.05$) among storage times. Different lowercase letters represent differences ($p < 0.05$) among UV-C doses within the same storage time. An interaction was observed between UV-C dose and storage time ($p < 0.05$, two-way ANOVA), indicating distinct temporal dynamics in color preservation efficacy across different UV-C dosage treatments

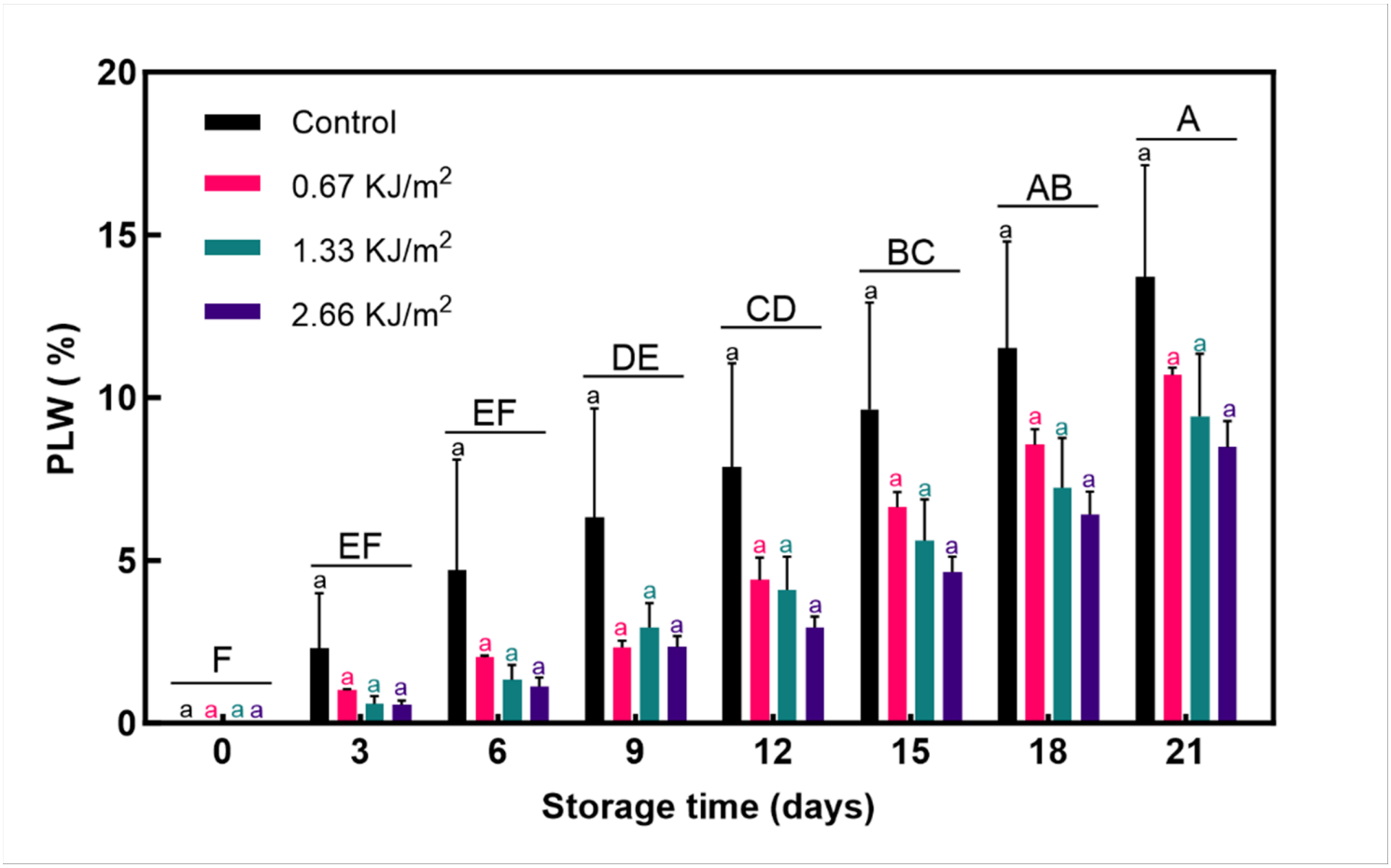

Figure 2

Dose-dependent effects of UV-C on the weight loss of shiitake mushrooms during storage. Different capital letters indicate differences ($p < 0.05$) among storage periods. Different lowercase letters denote differences ($p < 0.05$) among UV-C doses within the same storage period. No interaction was observed between UV-C dose and storage time ($p > 0.05$, two-way ANOVA), indicating the absence of distinct temporal patterns in weight loss across different UV-C dosage treatments

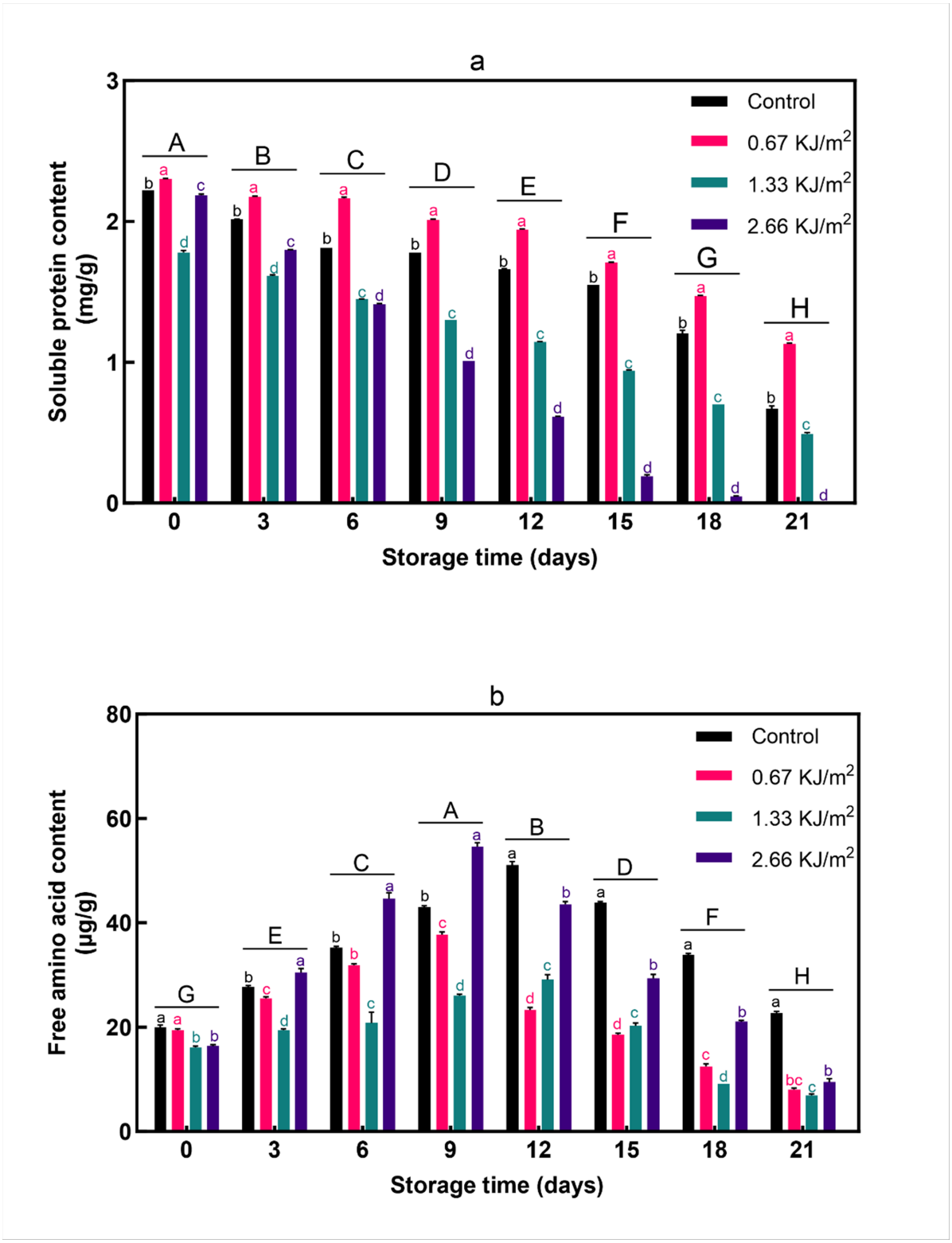

Figure 3

Dose-dependent effects of UV-C treatment on soluble protein (a) and free amino acid (b) content in shiitake mushrooms during storage. Different capital letters indicate differences ($p < 0.05$) across storage periods; different lowercase letters denote differences ($p < 0.05$) among UV-C doses within the same storage period. An interaction between UV-C dose and storage time ($p < 0.05$, two-way ANOVA)

was observed, indicating distinct temporal dynamics in both soluble protein and free amino acid content under different UV-C treatments

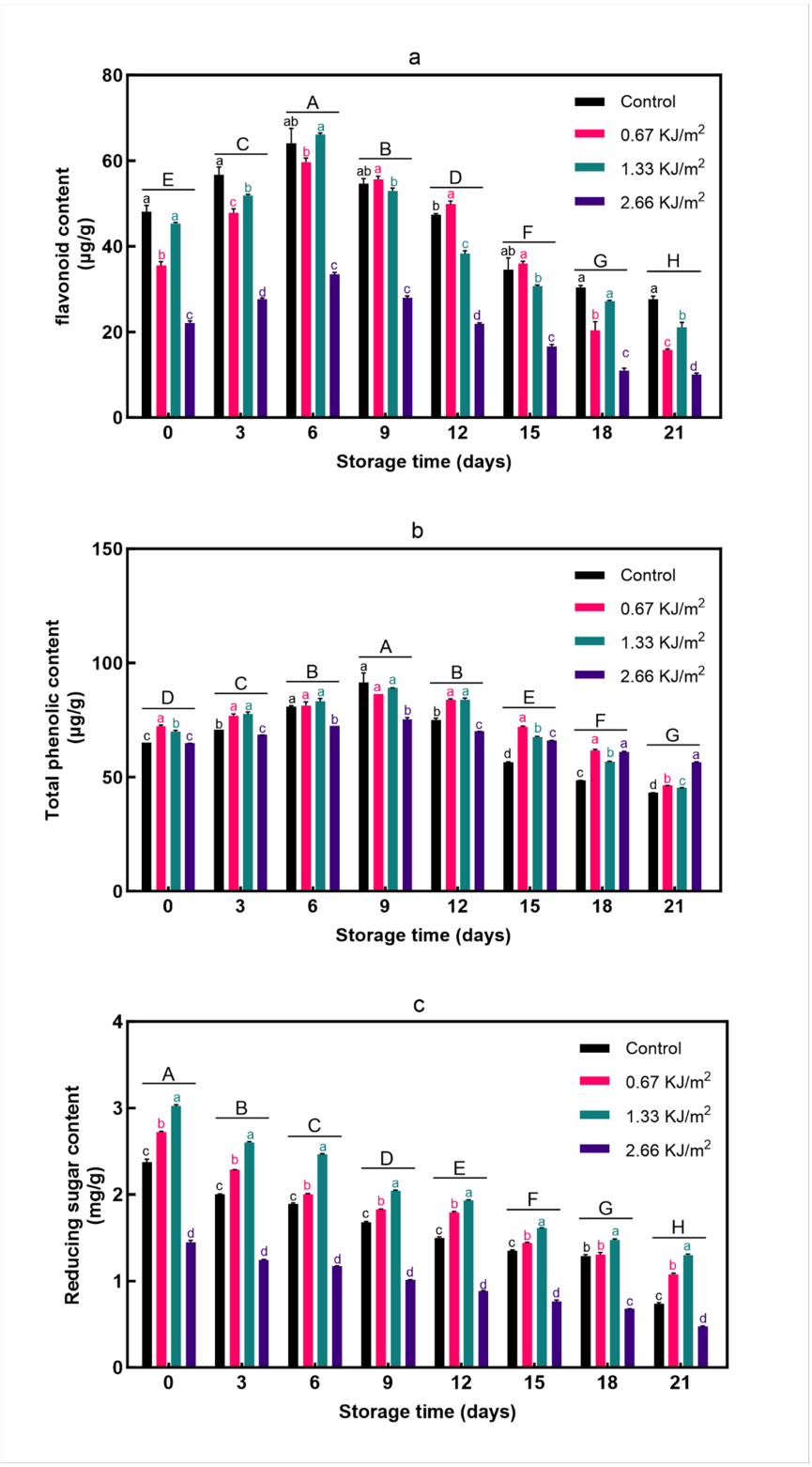

Figure 4

Effects of UV-C treatment dose on the contents of flavonoids (a), total phenolics (b), and reducing sugars (c) in shiitake mushrooms during storage. Different uppercase letters indicate differences over storage time within the same UV-C dose ($p < 0.05$); different lowercase letters indicate differences

among UV-C doses at the same storage time ($p < 0.05$). Two-way ANOVA revealed an interactive effect between UV-C dose and storage time ($p < 0.05$), indicating that the influence of UV-C treatment on these metabolites exhibited distinct time-dependent dynamics.

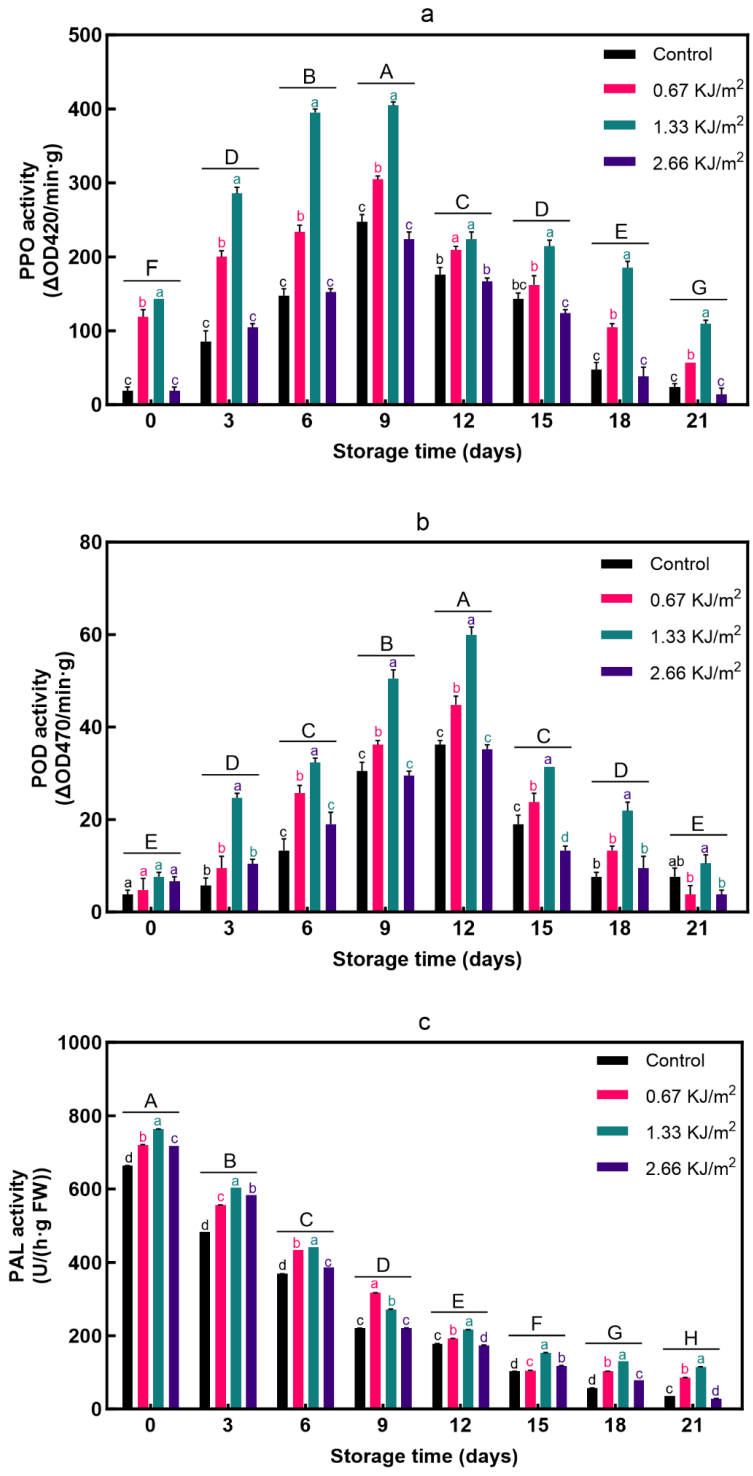

Figure 5

Effects of UV-C treatment dose on the activities of PPO (a), POD (b), and PAL (c) in shiitake mushrooms during storage. Different uppercase letters indicate differences over storage time within the same UV-C

dose ($p < 0.05$); different lowercase letters indicate differences among UV-C doses at the same storage time ($p < 0.05$). An interaction between UV-C dose and storage time was revealed by two-way ANOVA ($p < 0.05$), demonstrating that the effects of UV-C treatments on enzyme activities followed distinct time-dependent patterns

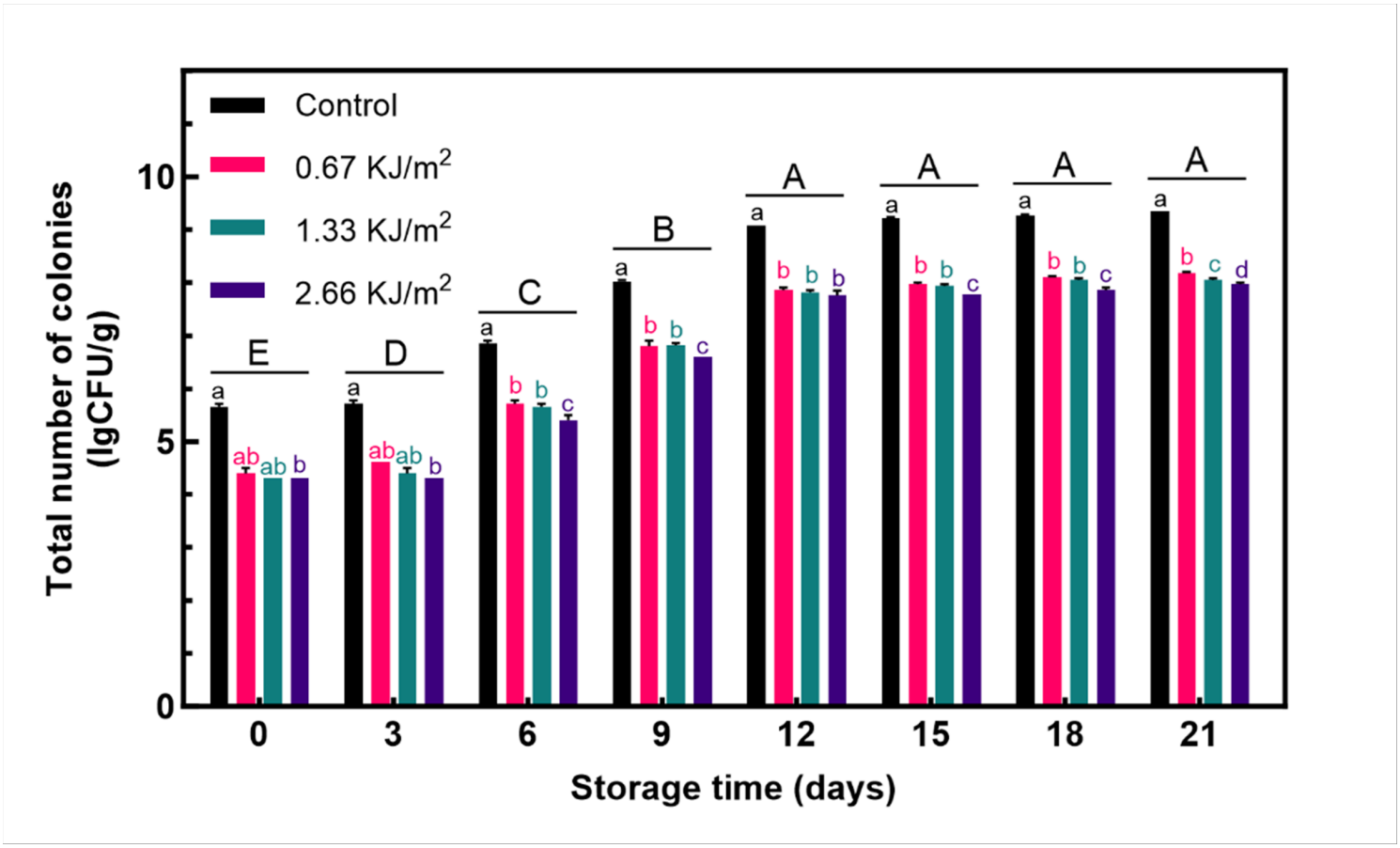

Figure 6

Effects of UV-C treatment dose on microbial indices of shiitake mushrooms during storage. Different uppercase letters indicate differences over storage time within the same UV-C dose ($p < 0.05$); different lowercase letters indicate differences among UV-C doses at the same storage time ($p < 0.05$). Two-way ANOVA revealed an interactive effect between UV-C dose and storage time ($p < 0.05$), indicating that the influence of UV-C treatment on microbial indices exhibited a distinct time-dependent pattern

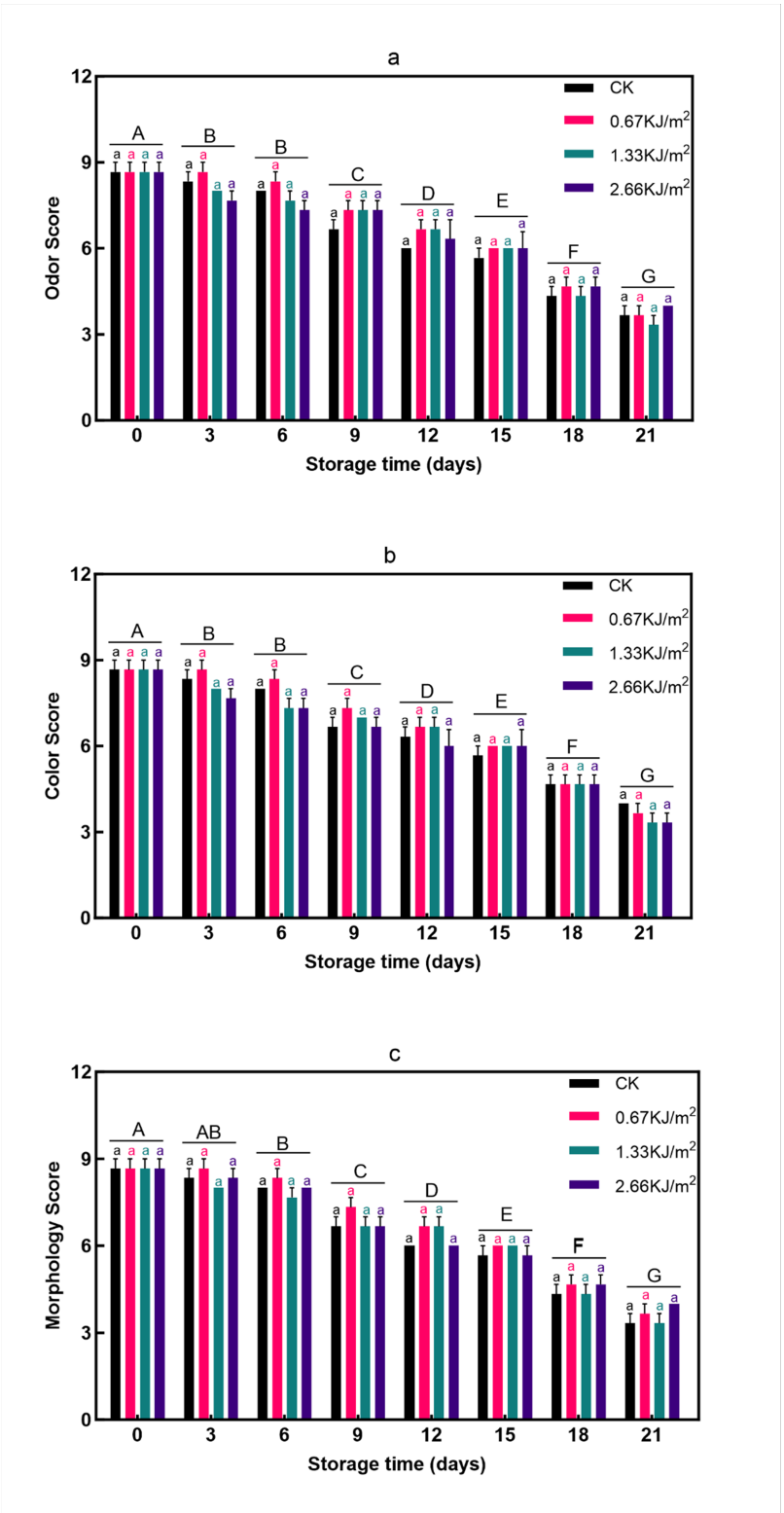

Figure 7

Effects of UV-C treatment dose on sensory evaluation indicators: odor (a), color (b), and morphology (c) of shiitake mushrooms during storage. Different uppercase letters indicate significant differences over storage time within the same UV-C dose ($p < 0.05$); different lowercase letters indicate significant differences among UV-C doses at the same storage time ($p < 0.05$). Two-way ANOVA showed no

significant interactive effect between UV-C dose and storage time ($p > 0.05$), indicating that the influence of UV-C treatment on sensory quality attributes did not follow a distinct time-dependent pattern