



Reducing Energy Consumption in Cold Storage of *Agaricus bisporus* Using Cactus Fruit Pigment-Enriched Edible Coating

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Abstract

Cold storage is one of the most energy-intensive stages in the postharvest management of fresh agricultural products such as edible mushrooms. Strategies that extend shelf life while preserving quality can effectively reduce refrigeration demand and improve energy efficiency in the agricultural supply chain. This study evaluated the impact of an edible coating enriched with cactus fruit pigment on the postharvest quality, microbial stability, and shelf life of *Agaricus bisporus* during cold storage, with an emphasis on energy-related implications.

Mushrooms were divided into three treatments: uncoated control ©, non-pigmented coating (NPC), and pigmented coating (PC). Samples were stored at 4 °C and 90% relative humidity for 10 days, and quality parameters including color attributes (L*, a*, b*), browning index, firmness, pH, polyphenol oxidase (PPO) and peroxidase (POD) activity, and total microbial load were monitored at regular intervals. The PC treatment significantly delayed browning, maintained higher L* values, reduced enzymatic activity, and lowered microbial counts by approximately 3 log CFU g⁻¹ compared with the control at day 10 (p < 0.05).

The improved quality retention resulted in an effective shelf-life extension of 3–4 days under refrigerated conditions, indicating a reduced need for intensive cooling and lower postharvest losses. These findings demonstrate that bio-based edible coatings enriched with natural pigments can function as a smart postharvest solution to enhance product quality

while indirectly contributing to reduced energy consumption in cold storage systems, supporting energy-efficient and sustainable agricultural production.

Keywords: Energy efficiency; Edible coating; Cold storage; Cactus fruit pigment; *Agaricus bisporus*

1. Introduction

In response to the growing demand for sustainable and natural food preservation strategies, edible coatings have emerged as a promising alternative to synthetic preservatives and conventional packaging systems (1,2). In addition to improving product quality, such approaches are increasingly valued for their potential to enhance resource efficiency and reduce postharvest losses in agricultural supply chains. When applied to the surface of fresh produce, edible coatings can act as semi-permeable barriers to moisture loss and gas exchange, thereby slowing respiration, delaying senescence, and reducing decay during refrigerated storage (3,4). By maintaining quality over longer storage periods, these systems may indirectly contribute to lower energy demand in cold storage facilities.

Natural pigments have recently attracted attention not only as colorants but also as functional food ingredients with bioactive properties (5,6). Among these, cactus fruit (*Opuntia* spp.), commonly known as prickly pear, is a rich source of betalains—water-soluble, nitrogen-containing pigments with strong antioxidant capacity and reported antimicrobial activity (7–9). Previous studies have demonstrated that betalain-rich extracts can suppress enzymatic browning by reducing polyphenol oxidase activity and scavenging reactive oxygen species, thereby preserving visual and textural quality during storage (10–12).

Extending the shelf life of highly perishable commodities such as edible mushrooms is particularly important due to their high respiration rate and sensitivity to storage conditions. Quality deterioration during cold storage often necessitates intensified refrigeration and leads to increased energy consumption and product losses. Therefore, developing postharvest technologies that preserve quality while enabling more efficient use of refrigerated storage is of growing interest. In this context, the present study aimed to investigate the incorporation of cactus fruit pigment into an edible coating to enhance the postharvest quality and extend the shelf life of *Agaricus bisporus* during refrigerated storage (13–15). By leveraging the natural protective properties of cactus pigments, this work aligns with current trends in bio-based preservation strategies and supports sustainable, energy-efficient postharvest management systems (16,17).

2. Materials and Methods

2.1. Mushroom Sample Preparation and Treatment Application

Freshly harvested *Agaricus bisporus* mushrooms of uniform size and maturity were obtained from a commercial producer (18). Upon arrival, samples were inspected to ensure the absence of mechanical damage or visible decay (19), as such defects can accelerate deterioration and increase cooling demand during storage. The edible coating base solution was prepared under sterile conditions using a plant-derived polysaccharide matrix (20), selected for its suitability in sustainable postharvest applications.

2.1.1. Three treatment groups were established:

2.1.1.1. Control ©:

Uncoated mushrooms stored under identical conditions to coated samples, representing conventional cold storage practice (21).

2.1.1.2. Non-Pigmented Coating (NPC):

Mushrooms coated with the base formulation without cactus pigment by dipping for 2 min (22).

2.1.1.3. Pigmented Coating (PC):

Mushrooms coated with the same base formulation enriched with 1% (w/v) cactus fruit pigment extract, prepared according to Gupta et al. (18), and applied using the same dipping method (23).

After coating, samples were allowed to drain and air-dry at ambient laboratory temperature (approximately 20 °C) for 30 min to ensure coating stabilization prior to packaging.

2.2.Storage Conditions

All samples were packaged in breathable polyethylene trays and covered with perforated plastic film to permit limited gas exchange while maintaining high relative humidity. Packaged mushrooms were stored in a controlled-environment chamber at 4 °C and 90% relative humidity (RH). These conditions reflect typical refrigerated storage settings used in commercial postharvest handling, where energy consumption is strongly influenced by storage duration and product respiration rate.

2.3.Sampling and Quality Assessment

Samples from each treatment were collected at Day 0, 2, 4, 6, 8, and 10 of storage. At each sampling point, a minimum of three replicates per treatment was analyzed to ensure statistical reliability and to monitor quality changes over time that may influence storage efficiency and shelf-life management decisions.

2.3.1.The following parameters were evaluated:

2.3.1.1.Color Parameters (L, a, b*):**

Color measurements were performed using a calibrated colorimeter (e.g., Konica Minolta Chroma Meter CR-400). Readings were taken from the cap surface of at least five mushrooms per replicate under consistent illumination and viewing geometry. CIE L* (lightness), a* (green–red), and b* (blue–yellow) values were recorded.

2.3.1.2.Browning Index:

The browning index was quantified using image analysis or a spectrophotometric method based on absorbance at selected wavelengths associated with enzymatic browning pigments. This index provided a direct indicator of quality deterioration during refrigerated storage.

2.3.1.3.Enzyme Activity (PPO and POD):

Polyphenol oxidase (PPO) and peroxidase (POD) activities were determined spectrophotometrically. Mushroom tissues were homogenized in appropriate buffer solutions, and enzyme activity was calculated based on substrate oxidation rates under standardized assay conditions. Results were expressed as units per minute per gram of fresh weight ($\text{U min}^{-1} \text{g}^{-1} \text{FW}$).

2.3.1.4.Microbial Load:

Total aerobic microbial counts were determined using the standard plate count method. Serial dilutions of homogenized mushroom samples were plated on nutrient agar and incubated at 25 °C for 48–72 h. Microbial populations were expressed as log CFU g^{-1} .

2.3.1.5.Firmness:

Texture firmness was measured using a texture analyzer equipped with a suitable probe. A constant penetration force or depth was applied to the mushroom cap, and the maximum force required was recorded in Newtons (N).

2.3.1.6.pH:

The pH of mushroom tissue was measured using a calibrated digital pH meter after homogenization of samples in deionized water.

2.4.Experimental Design and Statistical Analysis

The experiment followed a completely randomized design (CRD). Data from three independent replicates per treatment and sampling day were analyzed using one-way analysis of variance (ANOVA). When significant differences were

observed ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) test was applied to compare treatment means. Statistical analyses were conducted using appropriate statistical software.

3.Results and Discussion

The application of edible coatings, particularly those enriched with cactus fruit pigment, had a pronounced and beneficial impact on the postharvest quality attributes of *Agaricus bisporus* during cold storage. The results obtained at the end of the 10-day storage period demonstrated significant differences across the tested parameters, highlighting the protective effects of the cactus pigment.

Table 1. Changes in Color Parameters (L^* , a^* , b^*) of Samples During 10 Days of Storage

Day	Sample	L^* (Mean $\pm$ SD)	a^* (Mean $\pm$ SD)	b^* (Mean $\pm$ SD)
0	C	92.1 ± 0.3^a	1.2 ± 0.1^a	15.2 ± 0.2^a
	NPC	92.3 ± 0.2^a	1.1 ± 0.1^a	15.1 ± 0.2^a
	PC	92.4 ± 0.2^a	1.1 ± 0.1^a	15.2 ± 0.1^a
10	C	74.5 ± 0.5^c	6.3 ± 0.2^a	18.5 ± 0.3^a
	NPC	78.3 ± 0.4^b	4.9 ± 0.2^b	17.8 ± 0.2^b
	PC	85.6 ± 0.3^a	2.5 ± 0.1^c	16.2 ± 0.3^c

- Values are expressed as mean $\pm$ standard deviation (SD).
- Different superscript letters (^{a-c}) within the same column indicate significant differences ($p < 0.05$).
- C: Control sample
- NPC: Non-optimal coated sample
- PC: Optimal coated sample

Values represent mean $\pm$ standard deviation ($n=3$). Means in the same column for Day 10 followed by different letters (a, b, c) indicate statistically significant differences ($p < 0.05$) according to Tukey's test.

3.1.Discussion on Color:

The initial color parameters (Day 0) were similar across all treatments, indicating a uniform starting material. However, by Day 10, significant changes were observed. The Control (C) group exhibited the lowest L value ($74.5 \pm 0.5c$), signifying a substantial loss of lightness, consistent with browning and general deterioration. The Non-Pigmented Coating (NPC) group showed a moderately improved L value ($78.3 \pm 0.4b$) compared to the control, suggesting that the coating matrix itself offered some protection against color loss. The Pigmented Coating (PC) group displayed the highest L^* value ($85.6 \pm 0.3a$) at Day 10, indicating the most effective preservation of lightness.

The a values, which represent the redness-greenness axis, increased considerably in the C and NPC groups ($6.3 \pm 0.2a$ and $4.9 \pm 0.2b$, respectively), indicating a shift towards red or brown hues due to enzymatic browning. In contrast, the PC group showed a significantly lower a value ($2.5 \pm 0.1c$), indicating that the cactus pigment effectively suppressed browning reactions. Similarly, the b values, representing the blueness-yellowness axis, increased in the C and NPC groups ($18.5 \pm 0.3a$ and $17.8 \pm 0.2b$), which is often associated with yellowing or brown pigment formation. The PC group maintained a much lower b value ($16.2 \pm 0.3c$), demonstrating superior retention of the characteristic white/offwhite color of the mushroom. The antioxidant properties of betalains in the cactus pigment likely played a key role in scavenging free radicals and inhibiting the enzymatic oxidation of phenolic compounds, which are the primary cause of browning in mushrooms.

Table 2. Qualitative Trend of Color Parameters (L*, a*, b*) During Storage

Color Parameter	Control ©	Non-Pigmented Coating (NPC)	Pigmented Coating (PC)
L* (Lightness)	Sharp decrease over storage time	Moderate decrease over storage time	Slight decrease / relatively stable
a* (Redness)	Significant increase	Noticeable increase	Slight increase / nearly constant
b* (Yellowness)	Significant increase	Moderate increase	Minimal change

Qualitative description of the trend of color parameters (L*, a*, and b*) in control ©, non-pigmented coating (NPC), and pigmented coating (PC) samples during storage. The pigmented coating treatment exhibited better color stability, particularly in maintaining lightness (L*) and inhibiting increases in a* and b* values associated with browning.

Table 3. Changes in PPO and POD Enzyme Activities (U/min/g FW) During Storage

Day	Sample	PPO (U/min/g FW)	POD (U/min/g FW)
0	C	12.1 ± 0.3 ^a	8.9 ± 0.2 ^a
	NPC	12.2 ± 0.2 ^a	8.9 ± 0.1 ^a
	PC	12.1 ± 0.3 ^a	8.8 ± 0.2 ^a
10	C	28.5 ± 0.4 ^a	19.8 ± 0.4 ^a
	NPC	23.3 ± 0.3 ^b	16.2 ± 0.3 ^b
	PC	16.4 ± 0.2 ^c	12.1 ± 0.2 ^c

- Values are expressed as mean ± standard deviation (SD).
- Different superscript letters (^{a-c}) within the same column indicate significant differences ($p < 0.05$).
- PPO: Polyphenol oxidase
- POD: Peroxidase
- C: Control
- NPC: Non-pigmented coating
- PC: Pigmented coating

The activities of PPO and POD significantly increased during storage in all samples. However, the pigmented coating (PC) treatment markedly suppressed enzyme activities compared to the control, indicating its effectiveness in delaying enzymatic browning and oxidative reactions during storage.

Values represent mean ± standard deviation (n=3). Means in the same column for Day 10 followed by different letters (a, b, c) indicate statistically significant differences ($p < 0.05$) according to Tukey's test.

3.2. Discussion on Enzyme Activity:

The initial enzymatic activity of PPO and POD was comparable across all treatments on Day 0. However, after 10 days of storage, significant differences emerged. The PPO activity in the Control group reached 28.5±0.4a U/min/g FW, indicating a substantial increase from the initial level. The NPC treatment resulted in a reduced PPO activity (23.3±0.3b U/min/g FW) compared to the control, suggesting a minor inhibitory effect from the coating matrix itself. Crucially, the PC treatment exhibited the lowest PPO activity (16.4±0.2c U/min/g FW), demonstrating a significant reduction in enzymatic browning potential. A similar trend was observed for POD activity. The control group showed the highest

activity ($19.8 \pm 0.4a$ U/min/g FW) at Day 10, followed by the NPC group ($16.2 \pm 0.3b$ U/min/g FW). The PC group maintained the lowest POD activity ($12.1 \pm 0.2c$ U/min/g FW). The effective inhibition of both PPO and POD by the cactus pigment coating can be attributed to the strong antioxidant properties of betalains. These compounds are known to scavenge reactive oxygen species (ROS) and can directly interact with and inactivate enzymes involved in oxidation processes, thus preserving the quality of the mushrooms.

Table 4. Qualitative Trend of PPO and POD Enzyme Activities During Storage

Enzyme	Control ©	Non-Pigmented Coating (NPC)	Pigmented Coating (PC)
PPO	Steady and sharp increase over storage time	Moderate increase over storage time	Slight increase; strongest inhibition
POD	Steady and sharp increase over storage time	Moderate increase over storage time	Minimal increase; highest stability

Qualitative description of changes in polyphenol oxidase (PPO) and peroxidase (POD) activities in control ©, non-pigmented coating (NPC), and pigmented coating (PC) samples during storage.

As shown in Table X, the activities of both PPO and POD enzymes exhibited an increasing trend during storage in all treatments. However, the rate of increase varied significantly among treatments. The control samples © showed the steepest increase in PPO and POD activities, indicating rapid progression of enzymatic browning and oxidative reactions during storage.

In contrast, samples treated with the non-pigmented coating (NPC) demonstrated a moderate increase in enzyme activities, suggesting partial inhibition of oxidative enzymes. Notably, the pigmented coating (PC) treatment exhibited the shallowest increase in both PPO and POD activities throughout the storage period, reflecting its superior inhibitory effect on enzymatic activity.

The reduced PPO and POD activities in PC-treated samples can be attributed to the presence of bioactive compounds in the pigmented coating, which may act as enzyme inhibitors and/or oxygen barriers, thereby delaying enzymatic browning reactions. These findings are consistent with the observed improvements in color stability (higher L* values and lower increases in a* and b*) in coated samples, highlighting a strong relationship between enzyme suppression and maintenance of visual quality during storage.

Table 5. Changes in Microbial Load and Firmness of Samples During Storage

Day	Sample	Microbial Load (log CFU/g)	Firmness (N)
0	C	3.1 ± 0.1 ^a	38.5 ± 0.4 ^a
	NPC	3.1 ± 0.1 ^a	38.4 ± 0.5 ^a
	PC	3.1 ± 0.1 ^a	38.6 ± 0.5 ^a
10	C	7.9 ± 0.2 ^a	21.3 ± 0.3 ^c
	NPC	6.5 ± 0.2 ^b	25.6 ± 0.3 ^b
	PC	4.8 ± 0.1 ^c	32.2 ± 0.4 ^a

- Values are expressed as mean ± standard deviation (SD).
- Different superscript letters (^{a–c}) within the same column indicate significant differences ($p < 0.05$).
- C: Control
- NPC: Non-pigmented coating
- PC: Pigmented coating

As presented in Table 5, the microbial load of all samples increased significantly during storage. However, the extent of microbial growth differed markedly among treatments. On day 10, the control samples © exhibited the highest microbial load (7.9 log CFU/g), indicating substantial microbial proliferation during storage. In contrast, samples treated with the non-pigmented coating (NPC) showed a moderate reduction in microbial load, while the pigmented coating (PC) treatment resulted in the lowest microbial count (4.8 log CFU/g), demonstrating a pronounced inhibitory effect against microbial growth.

Firmness decreased significantly in all samples over the storage period, reflecting typical postharvest softening. Nevertheless, the rate of firmness loss was strongly influenced by the applied coatings. The control samples showed the greatest reduction in firmness, decreasing to 21.3 N by day 10. Conversely, NPC-treated samples retained higher firmness, while the PC treatment most effectively preserved textural integrity, maintaining a firmness value of 32.2 N.

The superior performance of the pigmented coating can be attributed to its dual functionality as a physical barrier limiting moisture loss and oxygen diffusion, as well as the presence of bioactive compounds with antimicrobial properties. Moreover, the lower microbial load in PC-treated samples likely contributed to reduced enzymatic and structural degradation of the tissue, thereby enhancing firmness retention. These findings indicate a strong relationship between microbial inhibition and maintenance of textural quality during storage.

3.3. Discussion on Firmness:

Firmness is a critical quality attribute that directly impacts consumer acceptance. As expected, mushrooms lost firmness over the storage period due to enzymatic and microbial activity, as well as water loss. On Day 10, the Control group had the lowest firmness (21.3±0.3c N), indicating significant softening. The NPC treatment provided some protection, with firmness retained at 25.6±0.3b N. The PC treatment was most effective in maintaining firmness, with the mushrooms retaining a significantly higher firmness of 32.2±0.4a N. This improved firmness retention in the PC group is likely a consequence of the coating's ability to reduce water loss, slow down enzymatic degradation of cell wall components, and inhibit microbial activity that can also lead to textural breakdown. The antioxidant action of the cactus pigment may also contribute by reducing oxidative damage to cellular structures.

Table 6. Qualitative Trend of Microbial Load Changes During Storage

Parameter	Control ©	Non-Pigmented Coating (NPC)	Pigmented Coating (PC)
Microbial load (log CFU/g)	Rapid and pronounced increase over storage time (steep slope)	Moderate increase over storage time	Slight increase; strongest inhibition of microbial growth

Qualitative description of microbial load trends in control ©, non-pigmented coating (NPC), and pigmented coating (PC) samples during storage.

As summarized in Table 6, microbial load increased progressively in all treatments throughout the storage period, which is consistent with the natural growth behavior of microorganisms in fresh food matrices. However, the rate of microbial proliferation differed substantially among treatments. The control samples © exhibited the steepest increase in microbial load, indicating rapid microbial growth in the absence of any protective coating.

Samples treated with the non-pigmented coating (NPC) showed a noticeably lower growth rate compared to the control, suggesting a partial inhibitory effect, likely due to the formation of a physical barrier that limited oxygen and moisture exchange. In contrast, the pigmented coating (PC) treatment demonstrated the shallowest increase in microbial load during storage, reflecting the strongest antimicrobial performance among all treatments.

The enhanced microbial inhibition observed in PC-treated samples can be attributed to the combined effects of barrier properties and the presence of bioactive compounds with antimicrobial activity. This reduction in microbial growth is in good agreement with the lower enzymatic activity (PPO and POD) and improved firmness retention observed in coated samples, highlighting the pivotal role of microbial control in maintaining overall postharvest quality during storage.

Table 7. Qualitative Trend of Firmness Retention During Storage

Parameter	Control ©	Non-Pigmented Coating (NPC)	Pigmented Coating (PC)
Firmness (N)	Rapid and pronounced decrease over storage time	Moderate decrease over storage time	Slight decrease; highest firmness retention

Qualitative description of firmness retention in control ©, non-pigmented coating (NPC), and pigmented coating (PC) samples during storage.

As summarized in Table 7, firmness decreased progressively in all treatments throughout the storage period, which is a typical postharvest phenomenon associated with tissue softening. However, the magnitude of firmness loss differed significantly among treatments. The control samples © exhibited the most pronounced decline in firmness, indicating rapid degradation of cell wall structure and loss of tissue integrity during storage.

Samples treated with the non-pigmented coating (NPC) showed a moderate reduction in firmness, suggesting that the coating provided partial protection by acting as a semi-permeable barrier that reduced moisture loss and delayed structural breakdown. In contrast, the pigmented coating (PC) treatment demonstrated the highest retention of firmness, with only a slight decrease in the force required for penetration over time.

The superior firmness preservation observed in PC-treated samples can be attributed to the synergistic effects of the coating matrix and the incorporated bioactive compounds, which likely reduced water migration, limited oxygen diffusion, and suppressed microbial activity. The lower microbial load and reduced enzymatic activity (PPO and POD) previously observed in PC-treated samples further support the close relationship between microbial inhibition, enzymatic control, and maintenance of tissue firmness. Overall, these results highlight the effectiveness of the pigmented coating in preserving textural quality and extending the postharvest shelf life of the product.

4. Conclusion

This study demonstrated that the application of an edible coating enriched with cactus fruit pigment is an effective approach for enhancing postharvest quality and extending the shelf life of *Agaricus bisporus* during cold storage at 4 °C and 90% RH. Compared with uncoated mushrooms and those treated with a non-pigmented coating, the pigmented coating (PC) showed superior performance in preserving key quality attributes throughout the storage period.

The PC treatment significantly maintained visual quality by retaining higher L* values and lower a* and b* values, indicating a pronounced delay in enzymatic browning and improved color stability. In addition, the activity of browning-related enzymes, including polyphenol oxidase (PPO) and peroxidase (POD), was markedly reduced, confirming the role of cactus pigment compounds in limiting oxidative discoloration. Microbial growth was also effectively controlled in the PC-treated samples, resulting in lower microbial loads and contributing to enhanced microbial stability. Furthermore, mushrooms coated with cactus pigment exhibited better firmness retention, reflecting a slower rate of textural degradation during refrigerated storage.

Beyond quality preservation, the observed extension of shelf life by approximately 3–4 days has important implications for refrigerated storage management. Prolonged maintenance of acceptable quality can reduce the need for intensive cooling, frequent product turnover, and premature disposal during cold storage, thereby contributing to improved energy efficiency and reduced postharvest losses. The combined barrier function of the edible coating and the antioxidant and antimicrobial properties of cactus betalains provides a sustainable, bio-based strategy that aligns with energy-efficient and smart agricultural practices. Overall, this approach offers a practical solution for enhancing product quality while supporting more sustainable and energy-conscious postharvest systems. Future research may focus on optimizing coating formulations and evaluating their performance under different storage and supply-chain conditions.

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