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RESEARCH

# Stability of Dried Pumpkin Snacks Packed in Bio-polymeric Films Through Accelerated Shelf-Life Testing

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## Abstract

This research evaluated the storage characteristics of dried pumpkin packed in two different films: polylactic acid (PLA) and polyethylene (PE) by accelerated shelf-life testing (ASLT) at three storage temperatures: 30, 40, and 50 °C. Weight loss, pH, water activity, color, and total microbial count of the samples were monitored at fixed times during the experiments. After 2 days of storage at 50 °C, the weight loss for the PLA and PE packaging reached its maximum value at 9.15 ± 0.8% and 6.53 ± 1.6%, respectively. The microbiological results demonstrated that, with a total plate count of fewer than 4 log CFU/g, the dried pumpkin samples did not degrade while being stored at different temperatures. Bioactive compound content (total polyphenols, ascorbic acid content, and carotenoid content) and antioxidant activity were determined at the end of storage, and they significantly changed with higher temperatures. The largest total polyphenols losses were observed for samples PLA 40 °C and PLA 50 °C (40%) and samples PE 50 °C (55%). For both packaging under the same storage conditions, antioxidant activity and ascorbic acid concentration likewise showed a similar pattern. The color changes observed during the storage were described by the non-enzymatic browning process using a pseudo-first-order reaction in terms of Chroma. The activation energy in terms of $Q_{10}$ (defined as the ratio of the rate constants when the temperature is raised by 10 °C) and the storage time at 25 °C were determined. The results showed that PLA film is an appropriate packaging for preserving the physico-chemical properties of dried pumpkin snacks.

**Keywords** Pumpkin · Drying · Storage · Accelerated shelf-life test · Packaging, Activation energy

## Introduction

In the context of consumers' increasing demand for high-quality food, the development of strategies to prolong the shelf-life of these products can attract the interest of the food industry and the processed food field. Moreover, consumers' awareness on environmental sustainability is increasing and leads to choose alternative packaging for food products. Bio-based polymeric films are eco-friendly, good alternatives of traditional plastic packaging (Indra Bhusan et al., 2020), and respond to the current requests of international legislative bodies for reducing plastic waste production.

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Pumpkin is widely cultivated in Italy throughout many regions and in many temperate climate areas of the world. It has high nutritional value because it is rich in antioxidants, vitamins, minerals, fibers, polysaccharides, and other compounds beneficial to human health. Furthermore, it is recommended in diets because of its low calorie content (Kaur et al., 2020; Shelke et al., 2015).

After harvesting, pumpkins are stable for 1–3 months, but after peeling, they are more perishable and rapidly lose organoleptic quality for microbial spoilage, softening, moisture loss, and color changes (Ripoli et al., 2021). For this reason, pumpkin is generally processed to obtain juice, pomace, pickles, and dried products in many countries worldwide (Adiletta et al., 2018; Hussain et al., 2022).

Drying is one of the most common processing technologies used to preserve and to increase the shelf-life of food products. The process considerably decreases the water activity of the material, reduces microbiological and enzymatic activities, and minimizes physical and chemical reactions during storage of dried foods (Proietti et al., 2018).

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Dried pumpkins can be used as a healthy snack, in breakfast cereals, or in traditional foods such as soups, biscuits, or desserts.

Moreover, drying combined with a pretreatment is an efficient method for reducing changes in color and antioxidant activity and for improving preservation (Adiletta et al., 2016a, b; Adiletta et al., 2018; Obajemihi et al., 2023; Önal et al., 2019; Xin et al., 2015; Zzaman et al., 2021).

In detail, pretreatment is widely used before drying of agro-products to inactivate enzymes, enhance drying process, and improve quality of dried products. The pretreatments include chemical solution (hyperosmotic, alkali, sulfite, and acid) and gas (sulfur dioxide, carbon dioxide, and ozone) treatments, thermal blanching (hot water, steam, super-heated steam impingement, ohmic and microwave heating, etc.), and non-thermal process (ultrasound, freezing, pulsed electric field, and high hydrostatic pressure) (Deng et al., 2019).

Among several pretreatments, the carbohydrate/salt solutions can be used as alternative pretreatment for biological systems for the drying process, resulting in shorter drying time and, hence, in lower energy requirements (Adiletta et al., 2018; Önal et al., 2019; Zzaman et al., 2021).

Among the carbohydrates, trehalose (non-reducing disaccharides) has recently received much attention owing to its many potential advantages in food industry such as protection of flavor and color, higher nutritional content and improvement of rehydration properties of dried fruits and vegetables. Trehalose confers to certain plant and animal cells the ability to survive dehydration and to restore activity soon after rehydration (Adiletta et al., 2016a, b; Santarelli et al., 2021; Zzaman et al., 2021). Moreover, immersing vegetables in sodium chloride solution before drying prevents the browning reaction and improves nutrient and color retention (Alipoorfard et al., 2020).

The shelf-life of dried foods, when properly stored, lasts from 4 to 12 months. Accelerated shelf-life test (ASLT) was performed in order to determine the shelf-life in a relatively shorter time. By this method, the product is stored under high stress conditions, such as high temperature, to accelerate the deterioration process. Accelerated shelf-life or stability tests are widely used in the process of developing new products in order to reduce time to market (Calligaris et al., 2019; Moufle et al., 2018).

In recent years, studies of shelf-life of foods by ASTL were carried out for fresh and fresh-cut vegetables (Li et al., 2022; Song et al., 2019; Zhao et al., 2022), fruit and vegetables purees and powder (Ancheta et al., 2020; Saarniit et al., 2023), and rainbow trout (Yin et al., 2022), but there is a lack of knowledge related to the shelf-life of packed dried vegetable snacks in biodegradable packaging.

Jiao et al. (2016) focused their attention on a common and conventional packaging for the storage of dried foodstuffs: vacuum packaging. They applied an accelerated shelf-life testing (ASLT) to speed up the quality deterioration of roast peanuts packaged in vacuum, but only at 50 °C for 4 weeks and considering the peroxide value as a quality indicator. In another study, Wongsa et al. (2023) evaluated the performances of two high-barrier-packing materials: laminated nylon with a low-density polyethylene bag (LDPE/nylon/LDPE) and laminated aluminum with a low-density polyethylene bag (LDPE/AL/LDPE) for dried garlic at high temperature of storage (30 and 50 °C). For dried food ingredients that are very sensitive to moisture, high-barrier-packaging materials are typically utilized (Kumar & Mishra, 2004).

However, the available research is very restricted to the biodegradable materials for packaging and storage conditions of pumpkin, which affect the physico-chemical parameters and bioactive compounds of packed dried pumpkin snacks during storage.

In this research the shelf-life of pretreated dried pumpkin slices, packed in a polyethylene bag (PE), as a reference, and in a biopolymeric bag of PLA (polylactic acid polymer from corn starch), was investigated by using the ASTL method. The objective was to evaluate the efficiency of the bio-packaging for the preservation of dried pumpkin compared to the plastic packaging through the evaluation of the main physico-chemical parameters (i.e., color, weight loss, microbiological counts) and bioactive compounds. After that, the color parameter changes in terms of chroma were used to predict the storage time because they were simple to calculate and an instantaneous signal of changes in product quality.

## Materials and Methods

### Samples Preparation

Pumpkins (*Cucurbita moschata*) were provided by a local farm (Tenuta di Dragone Corsetti, Rome, Italy). This cultivar is a medium-sized pumpkin with a weight between 8 and 15 kg that can be stored whole for more than 6 months after harvest. It has a reddish-ocher skin, with evident grooves and a very thick, tasty, and orange pulp.

The samples were harvested and transported within 2 h directly from the field to the laboratory under refrigerated conditions and stored at 10 °C until processing.

The pumpkins were washed with a sanitizer solution (2.5% of sodium bicarbonate) and cut into slices (6 mm of thickness) by means of electric slicer (H275, Fimar, Italy) and then by using a suitable steel mold (30 mm of diameter). The slices were pretreated by dipping, in an aqueous solution

of 0.8% (w/v) trehalose, 0.1% (w/v) NaCl, and 0.2% (w/v) sucrose for 5 min at 25 °C (Adiletta et al., 2018).

It was previously demonstrated that samples treated with this solution prior to drying showed a shorter (about 1/4) drying time, less volume shrinkage and color changes, and higher rehydration capacity compared to untreated ones, especially in the range 55–65 °C. Additionally, the pretreatment was successful in preserving antioxidant activity and total phenolic content (Adiletta et al., 2018).

Afterwards, the samples were dried in a laboratory oven at 60 °C for 24 h until they reached a constant weight and a water activity value of 0.33 ± 0.01. The dried pumpkin slices (5 g) were then packed in PE and PLA bags with a volume of 1000 $cm^3$.

## ASTL Protocol

The packed samples were placed in incubators set at three different temperatures: 30, 40, and 50 °C (Calligaris et al., 2019; Saarniit et al., 2023). The weight loss, water activity, pH, color, and microbiological parameters were monitored every 3 days for 12 days at 30 °C, every 3 days for 9 days at 40 °C, and every 2 days for 6 days at 50 °C.

The temperatures of 30, 40, and 50 °C were selected for drastically testing the samples (Calligaris et al., 2019; Saarniit et al., 2023). The duration of the test was determined by the time from the beginning of the experiment to the point at which the dried sample is declared inappropriate for one or more controlled indications.

The experimental design for accelerated shelf-life testing is reported in Table 1.

For each sampling date at 30, 40 and 50 °C, three biological replicates per treatment were prepared.

## Determination of Physical Parameters: Weight Loss, Water Activity, pH, and Color

The weight loss % was determined according to the following equation:

$$\%\, M_{\mathrm{LOSS}}(t) = \frac{M_0 - M_t}{M_0} \cdot 100 \tag{1}$$

where $\%\, M_{\mathrm{LOSS}}(t)$ is the weight loss % at time $t$, $M_0$ is the initial sample mass, and $M_t$ is the sample mass at time $t$. The sample mass was determined by a digital precision balance (± 0.01 g) (Gibertini, Crystal 500, Italy).

Two technical replicates were performed on each biological replicate.

Water activity was measured using a digital humimeter (Humimeter RH2, Schaller, Austria). The samples and the instrument were adjusted to the surrounding temperature (25 °C ± 1) for at least 30 min. Dried pumpkin sample (2.5 g) was placed in a thermostatic cell at 25 °C, and the measure was carried out after 10 min.

The pH was evaluated on the homogenized samples by a pH meter (GLP 21, Crison Instruments, Spain). Approximately 1 g of dried sample was homogenized into 20 mL of bidistilled by stirring for 30 min, and then, the pH of the supernatant was measured. Two technical replicates were performed on each biological replicate.

Pumpkin color was determined by readings on the two different faces of the slices, using a colorimeter (WR10QC, Beley, China), calibrated with a white standard tile. The CIELab coordinates ($L^*$, $a^*$, $b^*$) were recorded. The color coordinate $L^*$ gives the lightness ranged from black at 0 to white at 100. The chromaticity coordinate $a^*$ is for red (+) and green (−), while the chromaticity coordinate $b^*$ is for yellow (+) and for blue (−) (Berns, 2000). The polar coordinate Chroma that indicates the dullness/vividness of the product was calculated using the following formula:

$$C = \sqrt{a^{*2} + b^{*2}} \tag{2}$$

where $a^*$ and $b^*$ are the Cartesian coordinates.

Furthermore, the browning index (BI, denoting the development of brown pigments on the surface of pumpkins slices) was calculated according to the following equation (Coklar et al., 2018):

$$\mathrm{BI} = \frac{[100 * (X - 0.31)]}{0.17} \tag{3}$$

where $X = \frac{a - 1.75L}{5.645L + a - 3.012b}$

Two technical replicates were performed on each biological replicate.

## Microbiological Analysis

Each sample at fixed time during storage was analyzed for total aerobic bacteria (TPC) following the procedure

**Table 1** The experimental design for accelerated shelf-life testing at different sampling time (x) and various storage temperatures

| Temperature °C | Time (days) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 2 | 3 | 4 | 6 | 9 | 12 |
| 30 | x | | x | | x | x | x |
| 40 | x | | x | | x | x | |
| 50 | x | x | | x | x | | |

of Di Matteo et al. (2021). Five grams of each sample were aseptically taken, placed in a stomacher bag, diluted with 0.9% NaCl solution, and homogenized with a stomacher blender (Seward Stomacher 400 Circulator, England). Appropriate dilutions were performed, to evaluate microbial load. The total aerobic count was determined on 3 M® Petrifilm aerobic total count, after incubation at 30 °C for 24–48 h. Microbial data were expressed as logarithms of the number colony-forming units per g of sample (log CFU/g). Two technical replicates were performed on each biological replicate.

## Bioactive Compounds and Antioxidant Activity

After the storage at different temperatures, pumpkin samples were analyzed in terms of bioactive compounds and antioxidant activity.

The samples were homogenized in methanolic solution (methanol/water 80:20 v/v), and supernatant was used to determine polyphenols (POL) and antioxidant activity (AA). The Folin-Ciocalteu colorimetric method was used to determine POL, and the results were expressed as milligrams of gallic acid equivalents (GAE) per 100 g dried weight (Adiletta et al., 2022).

The antioxidant activity (AA) was determined by measuring the radical scavenging activity of 1,1-diphenyl-2-picrylhydrazil (DPPH) and 2.2′-azinobis-(3-ethylbenzothiazolin-6-sulphonic acid (ABTS) (Adiletta et al., 2022; Ferrara et al., 2022). The results were expressed in μmol Trolox equivalent (TE) per gram dried weight.

The ascorbic acid content (AsA) was determined following the method described by Adiletta et al. (2019) and expressed as mg ascorbic acid (AsA) per 100 g dried weight.

Total carotenoids (CAR) were extracted using 10 g of sample in methanol (1:10 w/v). At 666, 653, and 470 nm, the absorbance was determined, and CAR was calculated according Lichtenthaler and Wellburn (1983). The results were expressed in μg TC per 100 g of dried weight.

For each parameter, two technical replicates were performed on each biological replicate.

## Kinetics Model Based on Quality Change

Mathematical kinetics models are effective tools for monitoring quality changes with the storage time and the temperature, thus accurately predicting shelf-life. The quality change in food is caused by different reactions such as non-enzymatic browning. In this paper, the changes of dried pumpkins quality parameters, such as color parameters (Chroma), were studied by using a pseudo-first-order equation. According to previous studies in food products (Ancheta et al., 2020; Damasceno et al., 2008; Ibarz et al., 2000), the rate law applicable to the non-enzymatic browning process can be a pseudo-first (logarithmic) equation considering an equilibrium value of the Chroma for each temperature tested.

The equation is:

$$\frac{dC}{dt} = k\left(C - C_f\right) \tag{4}$$

where $C$ is the Chroma at the time $t$, $k$ is the rate constant (days$^{-1}$) that is a function of temperature, and $C_f$ is the Chroma at final time that depends on the storage temperature.

After integration, Eq. 3 became:

$$-\ln\frac{C - C_f}{C_0 - C_f} = kt = f(t) \tag{5}$$

where $C_0$ is the Chroma at time 0.

The activation energy $E_a$ of the non-enzymatic browning reaction for the dried pumpkin in PLA and PE bags was calculated by Arrhenius plot of ln(k) against 1/T together with the values of $Q_{10}$. The latter is defined as the ratio of the rate constants when the temperature is increased by 10 °C, and it shows how much faster the reaction proceeds with increasing temperature for every 10 °C. It can be obtained using the following equation:

$$ln\left(Q_{10}\right) = -\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T + 10°C}\right) \tag{6}$$

According to the studies of Lee and Krotchta (2002), when the shelf-life at a high-temperature $T_1$ was given, the shelf-life at room temperature $T_2$ was estimated given the rate constants at $T_1$ and $T_2$ for any reaction order:

$$k_1 t_{s1} = k_2 t_{s2} \tag{7}$$

where $k_1$ and $k_2$ are rate constants at $T_1$ and $T_2$, respectively, and $t_{s1}$ and $t_{s2}$ are shelf-life values at $T_1$ and $T_2$, respectively. Using Eq. 4, the shelf-life time at 25 °C ($t_{s1}$) was calculated by the Arrhenius equation in the following form:

$$\ln\frac{t_{S1}}{t_{S2}} = \frac{E_a}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \tag{8}$$

## Statistical Analysis

All analyses were performed at each sampling date during storage on two technical replicates for each biological replicate (three). The results reported as mean values ± standard deviation (SD). Data were analyzed by using the one-way analysis of variance (ANOVA). The significance of differences ($p < 0.05$) among samples was determined by the Tukey test. All analyses were performed using the SPSS software package, version 27.0.1 (SPSS Inc., USA).

## Results and Discussion

### Weight Loss

At the end of storage, the weight loss of pumpkin samples in PLA and PE packaging was plotted as a function of temperature in Fig. 1. The weight loss percentage significantly increased with the storage temperature. In details, PLA packaging showed higher mass loss values than PE packaging.

In both packaging, the weight loss reached the maximum value after 2 days of storage at 50 °C and after 3 days at 30 and 40 °C (data not reported). Afterwards, it remained constant up to the end of the tests.

At 30 and 40 °C, there were no differences in the final weight loss for PE packaging. However, the highest values for PLA and PE packaging, 9.15 ± 0.8% and 6.53 ± 1.6%, respectively, were recorded at 50 °C.

### Changes in Physical Parameters During Storage at Different Temperatures

Water activity ($a_w$) is considered one of the most important parameters in food preservation of dehydrated products. $A_w$ is the ratio of vapor pressure of water in a product to the vapor pressure of pure water at the same temperature and describes the unbound/available or free water of the food products. It is an important indicator for the shelf-life of the food products as it strongly influences the growth of microorganisms (Singh et al., 2015; Syamaladevi et al., 2016). Microorganisms will not grow below a certain $a_w$ level: 0.90 for most pathogenic bacteria, 0.70 for spoilage molds, and 0.60 for all microorganisms (Di Matteo et al., 2021).

The $a_w$ of dried pumpkin at time 0 was 0.332 ± 0.001; at 30 °C, in the first period of storage (3 days), the $a_w$ values decreased slightly with the temperature, reaching stability after 2–4 days, for both PLA and PE packaging. The $a_w$ measured in PLA package at 40 °C and 50 °C reached lower values (0.285 ± 0.002 and 0.283 ± 0.001, respectively) than PE (Table 2). This trend can be caused by higher permeability of PLA combined with higher storage temperatures.

From the literature, it is found that, at similar storage temperatures (30–50 °C), the $a_w$ changes occurred for dried banana samples packed in the PLA-based packaging to greater extent than metalized plastic film composed of oriented PP, metalized PET, and linear low-density PE layers (Phothapaeree et al., 2017).

The pH value of dried pumpkin at time 0 was 6.16 ± 0.05. During the storage, after 2 days at 50 °C and 3 days at 40 °C, pH values increased slightly for both PLA and PE packaging and then was stable up to end of trial. The variations of pH among samples were not statistically significant ($p < 0.05$), in the tested storage period.

In order to evaluate the extent of browning during ASTL trial, Chroma and the BI parameters were monitored in packed products. The browning degree increased over the storage time and with increasing temperature. The Chroma of the dried pumpkin changed from light orange/brown to

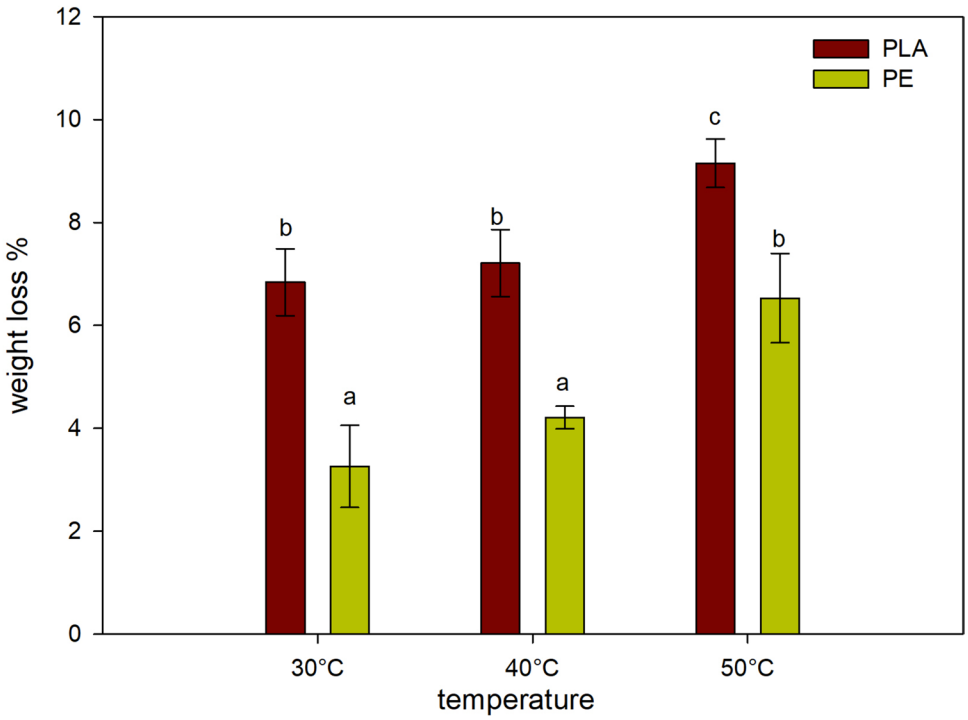


**Fig. 1** Weight loss (%) of dried pumpkin in PLA and PE bags, recorded at the end of storage at 30, 40, and 50 °C. Different lowercase letters indicate a significance ($p < 0.05$) among all samples

**Table 2** Mean values of physical parameters of dried pumpkin samples packaged in PLA and PE bags during storage at different temperatures

| Temperature in ASTL | Timing | $a_w$ | | pH | | Choma | | BI | |
|---|---|---|---|---|---|---|---|---|---|
| | | PE | PLA | PE | PLA | PE | PLA | PE | PLA |
| 30 | 0 | $0.332^{bE} \pm 0.007$ | $0.332^{bD} \pm 0.007$ | $6.16^{abA} \pm 0.01$ | $6.16^{abAB} \pm 0.01$ | $62.10^{dA} \pm 1.20$ | $62.10^{dF} \pm 1.20$ | $195.10^{aA} \pm 10.10$ | $195.10^{aA} \pm 10.10$ |
| | 3 | $0.312^{dD} \pm 0.003$ | $0.314^{dC} \pm 0.001$ | $6.20^{bcBC} \pm 0.02$ | $6.15^{aAB} \pm 0.01$ | $58.69^{bcBC} \pm 1.50$ | $60.19^{cdEF} \pm 0.65$ | $241.21^{bB} \pm 12.45$ | $251.85^{bB} \pm 14.10$ |
| | 6 | $0.315^{dD} \pm 0.003$ | $0.311^{aC} \pm 0.003$ | $6.20^{bcBC} \pm 0.02$ | $6.15^{aAB} \pm 0.01$ | $58.01^{bcBC} \pm 1.50$ | $58.43^{bcE} \pm 0.08$ | $254.38^{bBC} \pm 9.87$ | $257.18^{bB} \pm 10.20$ |
| | 9 | $0.311^{dD} \pm 0.003$ | $0.315^{aC} \pm 0.003$ | $6.21^{cC} \pm 0.02$ | $6.16^{abAB} \pm 0.01$ | $56.40^{abC} \pm 1.50$ | $57.56^{abcE} \pm 0.07$ | $259.70^{bBC} \pm 14.25$ | $285.71^{bB} \pm 20.10$ |
| | 12 | $0.310^{aCD} \pm 0.003$ | $0.316^{aC} \pm 0.003$ | $6.20^{bcBC} \pm 0.02$ | $6.15^{aAB} \pm 0.01$ | $54.43^{aBC} \pm 1.50$ | $54.62^{aD} \pm 0.08$ | $383.57^{dFG} \pm 15.40$ | $321.31^{cCD} \pm 14.10$ |
| 40 | 0 | $0.332^{cE} \pm 0.007$ | $0.332^{cD} \pm 0.007$ | $6.16^{aA} \pm 0.01$ | $6.16^{aAB} \pm 0.01$ | $62.10^{dA} \pm 1.20$ | $62.10^{dF} \pm 1.20$ | $195.10^{aA} \pm 10.1$ | $195.10^{aA} \pm 10.1$ |
| | 3 | $0.299^{bBC} \pm 0.001$ | $0.287^{aB} \pm 0.001$ | $6.25^{cD} \pm 0.01$ | $6.14^{abA} \pm 0.01$ | $57.19^{cD} \pm 1.00$ | $57.50^{cE} \pm 0.08$ | $282.06^{bCD} \pm 9.15$ | $286.99^{bBC} \pm 13.12$ |
| | 6 | $0.298^{bB} \pm 0.001$ | $0.285^{aB} \pm 0.001$ | $6.25^{cD} \pm 0.01$ | $6.14^{abA} \pm 0.01$ | $53.05^{abD} \pm 1.00$ | $54.60^{bD} \pm 0.03$ | $319.23^{cDE} \pm 14.35$ | $324.62^{cD} \pm 10.10$ |
| | 9 | $0.297^{bB} \pm 0.001$ | $0.2850^{aB} \pm 0.001$ | $6.26^{cD} \pm 0.01$ | $6.13^{aA} \pm 0.01$ | $52.01^{aD} \pm 1.00$ | $51.44^{aC} \pm 0.15$ | $323.72^{cE} \pm 10.18$ | $335.70^{cD} \pm 12.31$ |
| 50 | 0 | $0.332^{cE} \pm 0.007$ | $0.332^{cD} \pm 0.007$ | $6.16^{aA} \pm 0.01$ | $6.16^{aAB} \pm 0.01$ | $62.10^{cA} \pm 1.00$ | $62.10^{cF} \pm 1.20$ | $195.10^{aA} \pm 10.10$ | $195.10^{aA} \pm 10.10$ |
| | 2 | $0.278^{bA} \pm 0.002$ | $0.265^{aA} \pm 0.002$ | $6.21^{bC} \pm 0.01$ | $6.20^{bC} \pm 0.01$ | $47.40^{bC} \pm 1.00$ | $45.62^{bB} \pm 2.21$ | $348.71^{bEF} \pm 15.41$ | $380.67^{bcE} \pm 18.14$ |
| | 4 | $0.277^{bA} \pm 0.002$ | $0.264^{aA} \pm 0.002$ | $6.21^{bC} \pm 0.01$ | $6.21^{bC} \pm 0.01$ | $41.17^{aC} \pm 1.00$ | $42.22^{aA} \pm 0.09$ | $411.47^{cdG} \pm 2024$ | $441.04^{dF} \pm 13.45$ |
| | 6 | $0.277^{bA} \pm 0.002$ | $0.263^{aA} \pm 0.002$ | $6.21^{bC} \pm 0.01$ | $6.20^{bC} \pm 0.01$ | $40.80^{aC} \pm 1.00$ | $41.76^{aA} \pm 0.02$ | $451.47^{dH} \pm 16.25$ | $453.42^{dF} \pm 12.78$ |

At similar storage temperature, mean values with different lower case letters (a, b, c….) are significantly different ($p < 0.05$) between PLA and PE packaging during storage time. Mean values with different capital letters (A, B) in the same column are significantly different ($p < 0.05$) among all samples (at different temperatures) packed in PLA or between all samples packed in PE

dark brown during storage. Furthermore, significant differences ($p < 0.05$) in browning index were recorded among packaged during the storage period. A significant change in color was observed at 50 °C (after 2 days) and 30 °C and 40 °C (after 3 days) for both PLA and PE packaging tested (Table 2).

## Microbiological Analysis

The total microbial count was plotted as a function of storage time, at different temperatures, in Figs. 2 and 3 for the tested packaging. All samples had total plate count less than 4 log CFU/g (Health Protection Agency, 2009; Stannard, 1997). The findings showed that the dried pumpkin samples did not deteriorate while being stored at various temperatures, indicating that microbial growth was not a factor in determining the pumpkin's shelf-life during the period under consideration.

No spoilage was also discovered in solar-dried bananas kept in two types of packaging materials (PLA-based film and metalized film) at varying temperatures (30, 40, and 50 °C) for up to 6 months (Phothapaeree et al., 2017). The same results with total plate count below the detectable limits were found for pretreated dried carrot slices packed in high-density polyethylene (HDPE) and stored at 18.5–29.1 °C temperature and 44.4–60.4% relative humidity for 6 months (Sra et al., 2014).

## Evaluation of Bioactive Compounds and Antioxidant Activity

To maintain the quality of dried pumpkin samples throughout storage, the optimal combination of packaging material

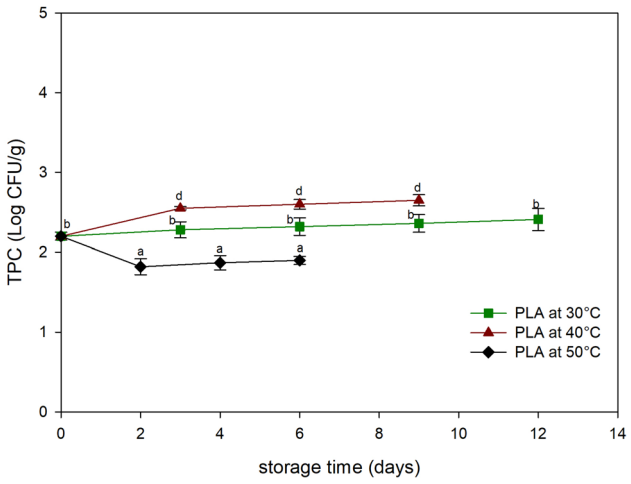


**Fig. 2** Total microbial count of dried pumpkin packed in PLA bags stored at different temperatures. Different lowercase letters indicate a significance ($p < 0.05$) among all samples

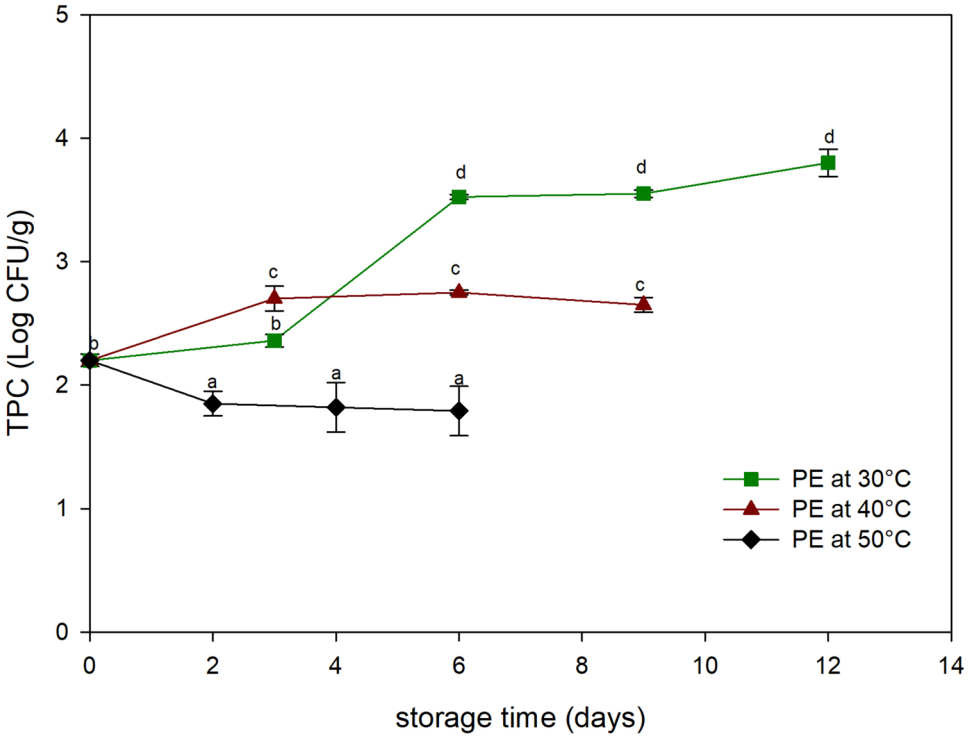


**Fig. 3** Total microbial count of dried pumpkin packed in PE bags stored at different temperatures. Different lowercase letters indicate a significance ($p < 0.05$) among all samples

and storage conditions must be selected. The number of bioactive compounds in dried samples after shelf-life tests is shown by the data in Table 3.

Higher storage temperatures (40 and 50 °C) resulted in significant losses of polyphenols (POL), antioxidant activity (AA), and ascorbic acid (AsA). As would be expected, the polyphenolic content decreased as storage temperature increased. The samples with the highest POL losses were PLA 40 °C and PLA 50 °C (40%) and PE 50 °C (55%). The DPPH antiradical activity was similar to ABTS antiradical activity. The trends of antioxidant activity (DPPH and ABTS) and ascorbic acid content also displayed a similar behavior of POL for both packaging under the same storage conditions.

However, after storage at different temperatures, the content of carotenoids (CARs) demonstrated greater stability with no significant differences with both packaging materials.

The effect of high storage temperature on bioactive compounds was also investigated by Siucinska et al. (2016). The anthocyanins in the osmo-dried sour cherries packed in polypropylene (PP) bags were found to be negatively affected by the time of storage (23, 45, and 68 days), with different deteriorating rate for each compound.

Furthermore, Wongsa et al. (2023) showed that the value and stability of phenolic compounds in dried garlic that was stored up to120 days at 10, 30, and 50 °C were greatly influenced by the temperature of storage.

**Table 3** Bioactive compounds and antioxidant activity in dried samples at the end of storage: polyphenols (POL: mg GAE/100 g DW), antioxidant activity (AA: µmol Trolox equivalent (TE)/g DW); total carotenoids (CAR: µg/100 g DW), ascorbic acid (AsA: mg/100 g DW)

| Sample | POL | $AA_{DPPH}$ | $AA_{ABTS}$ | CAR | AsA |
|---|---|---|---|---|---|
| PLA 30 °C | $305.90^{c} \pm 15.89$ | $3.29^{d} \pm 0.26$ | $29.7^{b} \pm 2.15$ | $3445.49^{a} \pm 318.15$ | $87.67^{ab} \pm 3.40$ |
| PLA 40 °C | $230.94^{ab} \pm 4.49$ | $2.77^{c} \pm 0.13$ | $25.63^{b} \pm 1.25$ | $2990.87^{a} \pm 446.29$ | $94.36^{ab} \pm 2.91$ |
| PLA 50 °C | $237.19^{ab} \pm 14.93$ | $2.25^{b} \pm 0.17$ | $18.63^{a} \pm 2.16$ | $3032.09^{a} \pm 193.06$ | $80.81^{a} \pm 3.14$ |
| PE 30 °C | $310.71^{c} \pm 9.96$ | $3.93^{e} \pm 0.02$ | $38.25^{c} \pm 3.22$ | $3582.62^{a} \pm 279.35$ | $133.62^{d} \pm 4.39$ |
| PE 40 °C | $276.25^{bc} \pm 21.36$ | $2.86^{cd} \pm 0.16$ | $26.71^{b} \pm 2.15$ | $3627.53^{a} \pm 479.43$ | $106.54^{bc} \pm 3.99$ |
| PE 50 °C | $182.71^{a} \pm 19.00$ | $1.69^{a} \pm 0.03$ | $10.32^{a} \pm 1.12$ | $3603.54^{a} \pm 319.84$ | $105.43^{bc} \pm 1.46$ |

*Different superscript letters (a, b) in the same column mean significant differences ($p < 0.05$)*

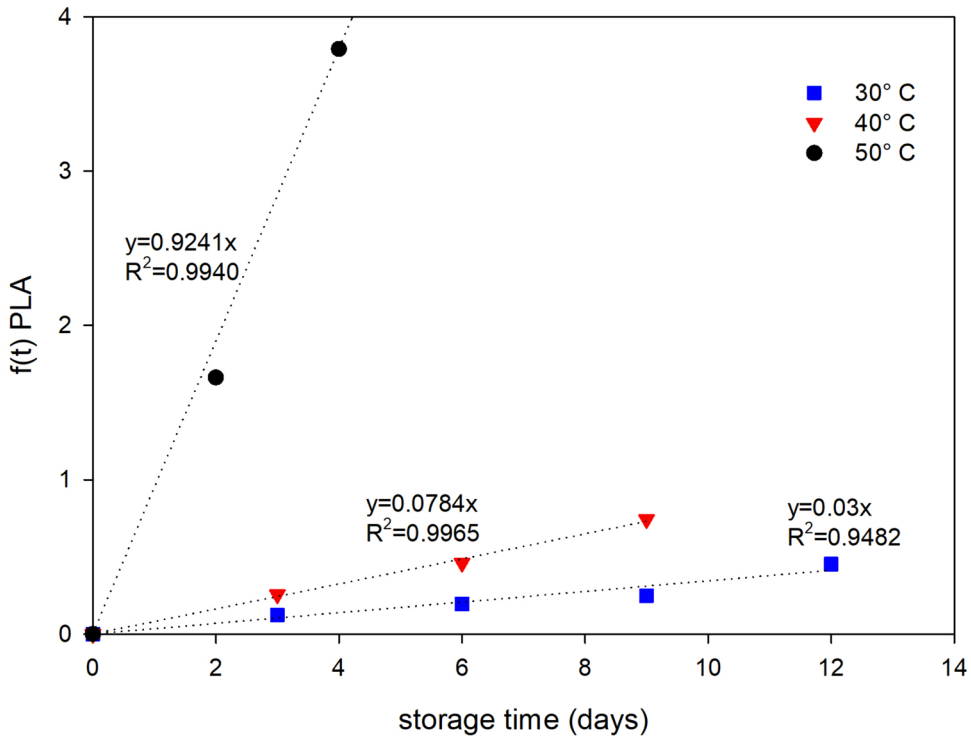


**Fig. 4** Linearized plots of f(t) against time at different temperatures for PLA packaging

Similar to how this study found that bioactive compounds and antioxidant activity decreased with storage temperatures up to 50 °C, Wongsa et al. (2023) also found that caffeic acid and ferulic acid decreased at 50 °C. In detail, the decrease of these phenolic acids was found higher in samples packed in low-density polyethylene (LDPE/nylon/LDPE) and laminated aluminum with a low-density polyethylene (LDPE/AL/LDPE) bags stored at 50 °C than in those stored at 10 and 30 °C (Wongsa et al., 2023).

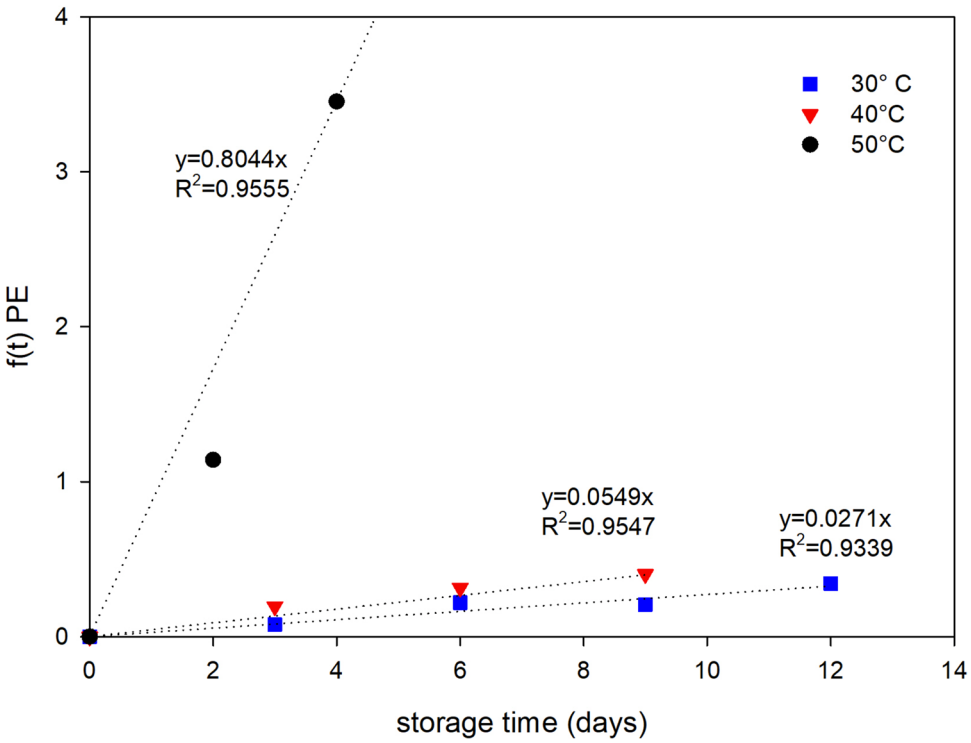


**Fig. 5** Linearized plots of f(t) against time at different temperatures for PE packaging

**Table 4** Values of Ea, $Q_{10}$, predicted shelf-life at 25 °C, and correlation factor $R^2$ obtained for the PE and PLA packaging

| Packaging | Ea (KJ/mol) | $Q_{10}$ | Shelf-life at 25 °C (days) | $R^2$ |
|---|---|---|---|---|
| PE | 137.04 | 6.02 | 289 | 0.8866 |
| PLA | 138.74 | 6.16 | 305 | 0.9296 |

### Kinetics of Non-enzymatic Browning of Dried Pumpkin and Shelf-Life Prediction at 25 °C

The results of ASTL data obtained for different parameters showed that the color is an important and immediate index of quality for dried pumpkins because it changes with temperature and time. The kinetics of non-enzymatic browning can be used for the mathematical description of the color changes. This process causes a brown color in foods due to caramelization and/or Maillard reactions, without the activity of enzymes.

In Figs. 4 and 5, linearized plot of *f(t)* (Eq. 5) is reported for PLA and PE, respectively.

The high $R^2$ values obtained for PLA (0.9482, 0.9965, 0.9940) and PE (0.9339, 0.9547, 0.9555) packaging showed that the reaction can be described by the pseudo-first-order equation proposed ($n=1$). The slopes of the linearized plotting are the $k$ values of the non-enzymatic browning reaction at various storage temperatures tested. The activation energy $E_a$ of the non-enzymatic browning reaction for the dried pumpkin in PLA and PE bags was reported in Table 4 together with the values of $Q_{10}$.

The little higher value of $E_a$ in biodegradable packaging PLA implied a little higher difficulty of the process to occur due to the packaging system and hence a greater stability of the food product.

In general, $Q_{10}$ values ranged from 1.5 to 2 for quality loss in canned foods, 1.5–3 for rancidity, and 4–10 for browning reactions (Labuza, 1984). The $Q_{10}$ values for the tested biodegradable (PLA) and classic packaging (PE) were in range for browning reaction with 6.16 and 6.02 values, respectively.

The values were comparable to those obtained from other studies on food products (Burdurlu & Karadeniz, 2003; Koca et al., 2003). Moreover, according the research of Taoukis et al. (1997), the non-enzymatic browning reaction will proceed more quickly with a lower activation energy value, which will result in a faster reduction in the quality of the dried pumpkin. This result indicates a greater stability to dried pumpkin in packaging system.

For both tested packaging, the calculations have been performed assuming a shelf-life time at 50 °C of 4 days, the sampling time in which the dried pumpkin snacks already significantly different from the time zero, in terms of color changes (Chroma). The shelf-life time values at 25 °C are reported in Table 4. Dried pumpkins packaged with biodegradable PLA film had a longer shelf life at 25 °C than dried pumpkins packaged in traditional PE (305 versus 289 days).

## Conclusions

In this study, the physical parameters, bioactive compounds, and antioxidant activity of dried pumpkin packaged in standard plastic film (PE) and biopolymeric film (PLA) were evaluated during the storage at different temperatures with the aim to study the shelf-life of the dried product.

The microbiological results revealed that the dried pumpkin snacks did not deteriorate when kept at different temperatures, suggesting that the shelf-life of the pumpkin during the period under review was not influenced by microbial development. By using biodegradable PLA packaging, the shelf-life is extended and the growth of microorganisms is slowed. Even though the bioactive compounds and antioxidant activity reduced as the temperature increased for both packaging types, at 50 °C, the biodegradable PLA packaging maintained these compounds better than the standard PE packaging. Taking into account all of the results, the shelf-life of dried pumpkin snacks, packed in PLA and PE bags, can be predicted using the ASLT by selecting the color as index of quality.

The packaging of dried pumpkin in PLA film is appropriate for preserving the physico-chemical properties of the product and provided a shelf-life time at 25 °C higher than polyethylene packaging (305 against 289 days). Overall, this study showed that, in order to reduce waste and protect the environment, biodegradable PLA film might be used in place of plastic PE film for dried pumpkin stored at 25 °C.

**Author Contribution** Giuseppina Adiletta: conceptualization; formal analysis; methodology; validation; visualization; writing, original draft; and writing, review and editing. Paola Di Matteo: formal analysis and investigation. Paola Russo: conceptualization, methodology, funding acquisition, resources, supervision, and writing—review and editing.

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**Data Availability** No datasets were generated or analyzed during the current study.

## Declarations

**Competing Interests** The authors declare no competing interests.

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